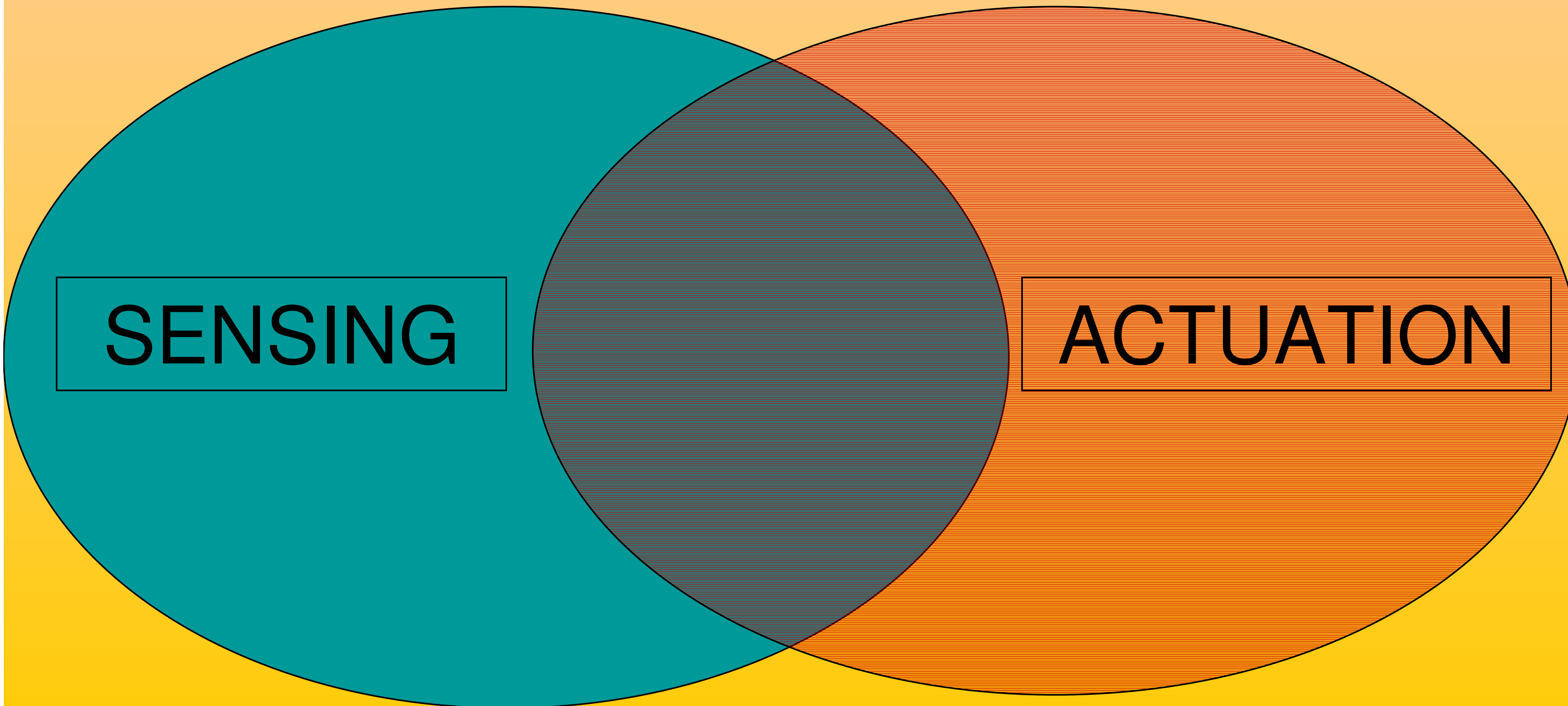
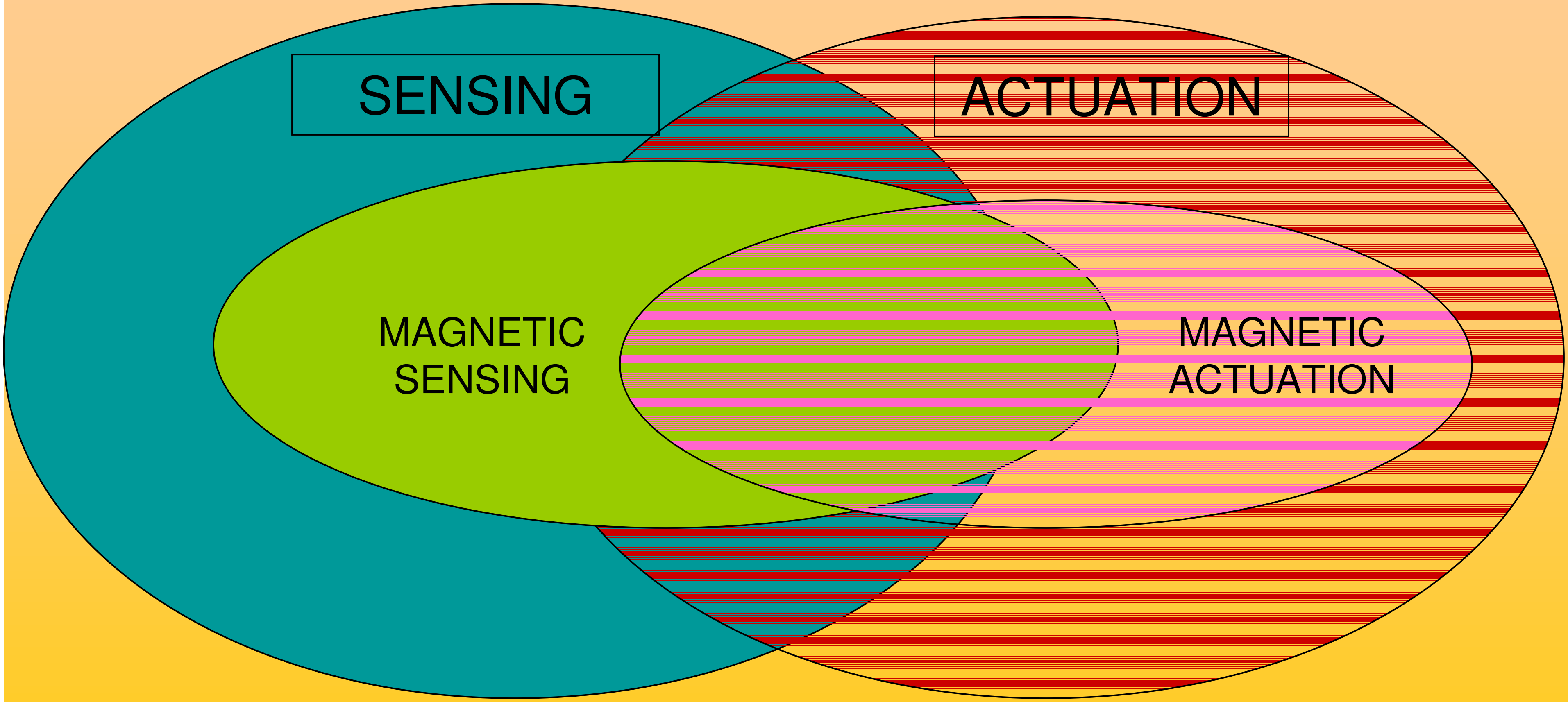
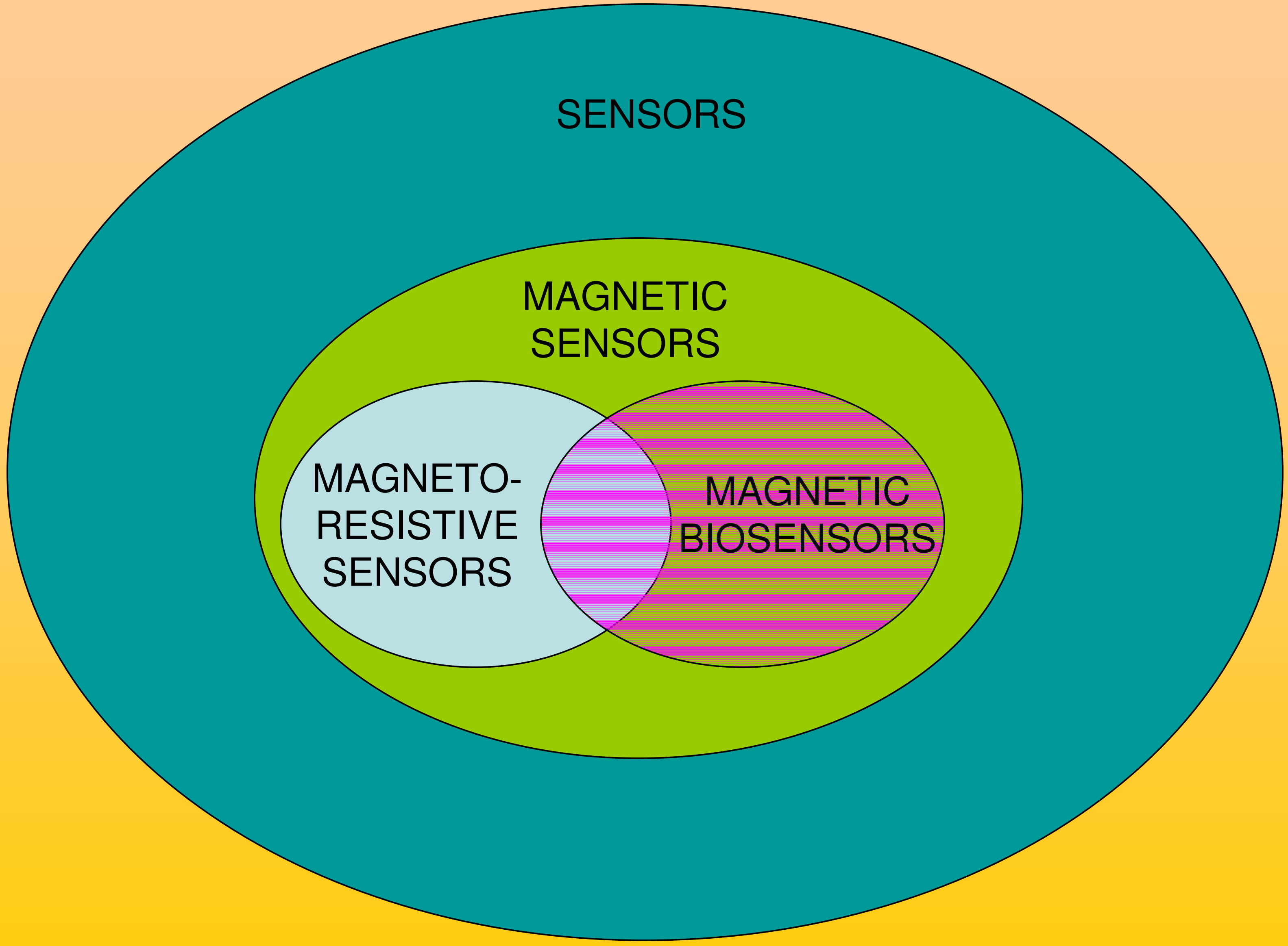
MAGNETIC SENSORS AND ACTUATORS

JOSE MARIA DE TERESA

(CSIC - UNIVERSIDAD DE ZARAGOZA, SPAIN)

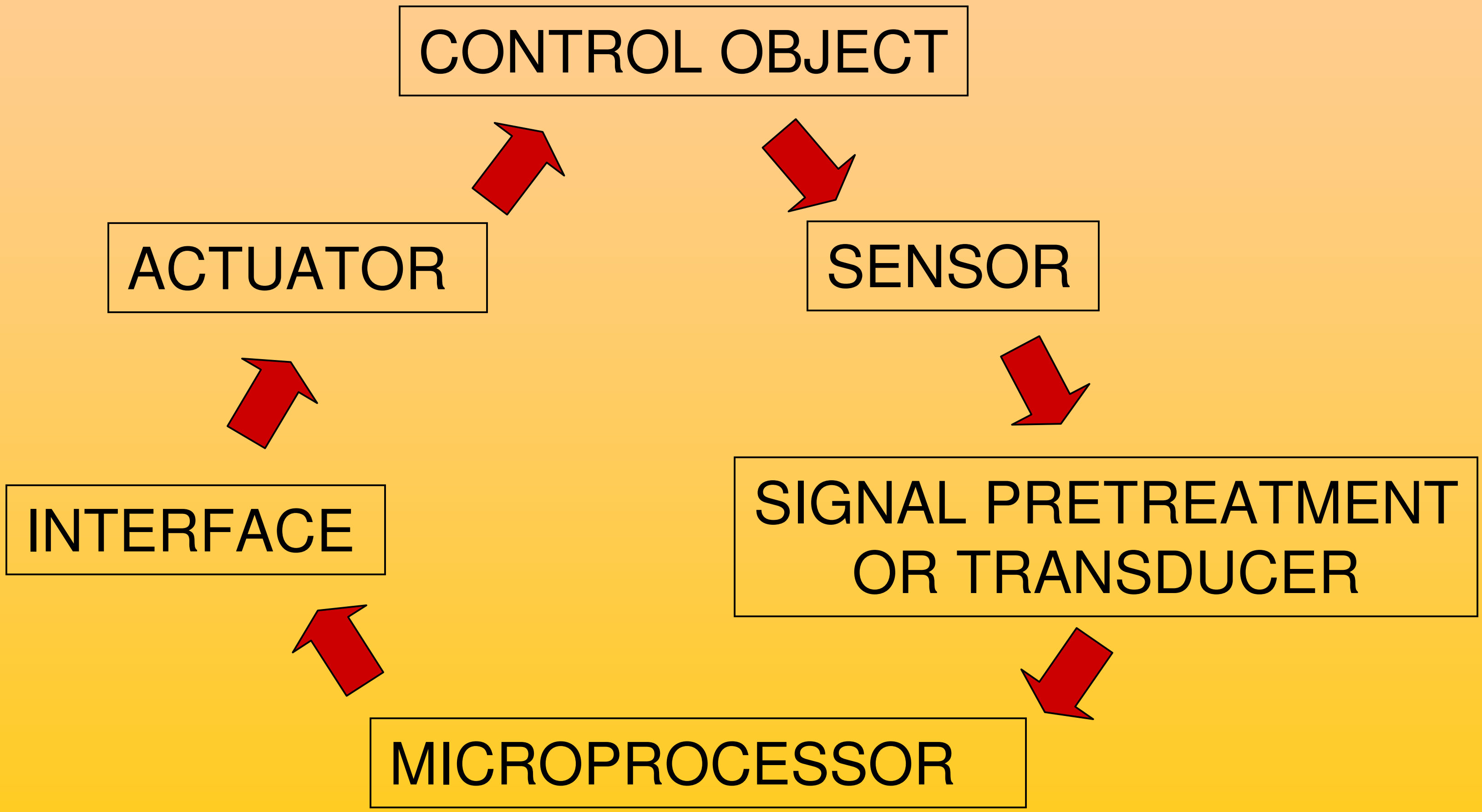



SENSING
ACTUATION
MAGNETIC
SENSING
MAGNETIC
ACTUATION


SENSORS
MAGNETIC SENSORS
MAGNETO-RESISTIVE SENSORS
MAGNETIC BIOSENSORS

INTRODUCTION TO SENSING AND ACTUATION

GENERAL SCHEME OF SENSING AND ACTUATION



WHAT MEANS SENSING?

TO DETECT PROPERTIES SUCH AS

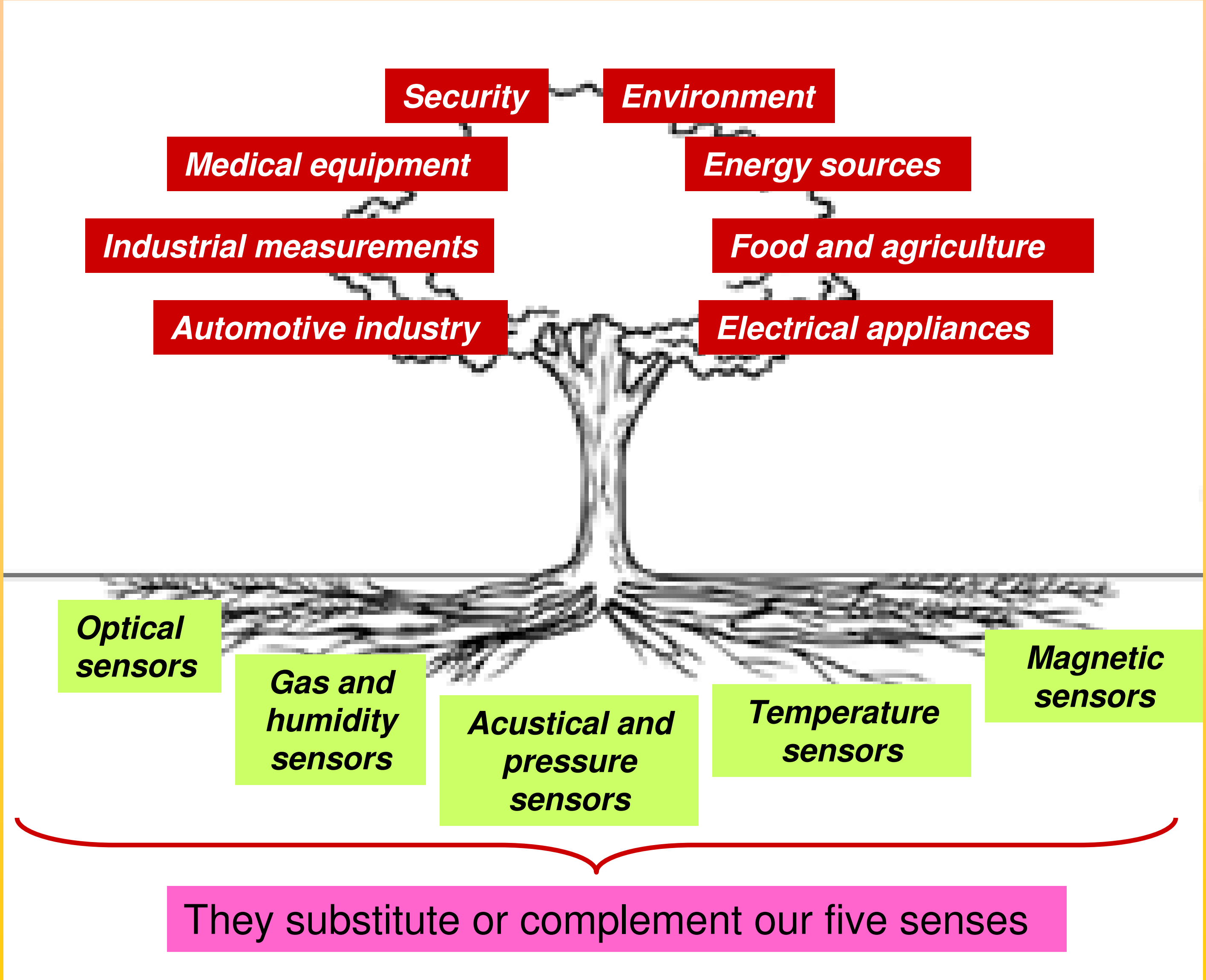
temperature, humidity, pressure, magnetic field, displacement, speed, chemical composition, light colour and intensity, etc.

BY MEANS OF A PHYSICAL OR CHEMICAL EFFECT

Sensing materials: ceramic, organic, metallic, composite, etc. and can be realized in bulk form or in thin-film form

thin-film → INTEGRATION

DOMAINS OF APPLICATION OF SENSORS



WHAT MEANS ACTUATION?

TO TRANSFORM AN INPUT SIGNAL (MAINLY ELECTRICAL) INTO MOTION

BY MEANS OF ELECTROMAGNETIC, PIEZOELECTRIC, MAGNETOSTRICTIVE, ELECTROSTRICTIVE,... EFFECTS

<u>Examples of actuators</u>: electrical motors, relays, electrovalves, piezoelectric actuators, etc. and can be realized in bulk form or with thin-film technology

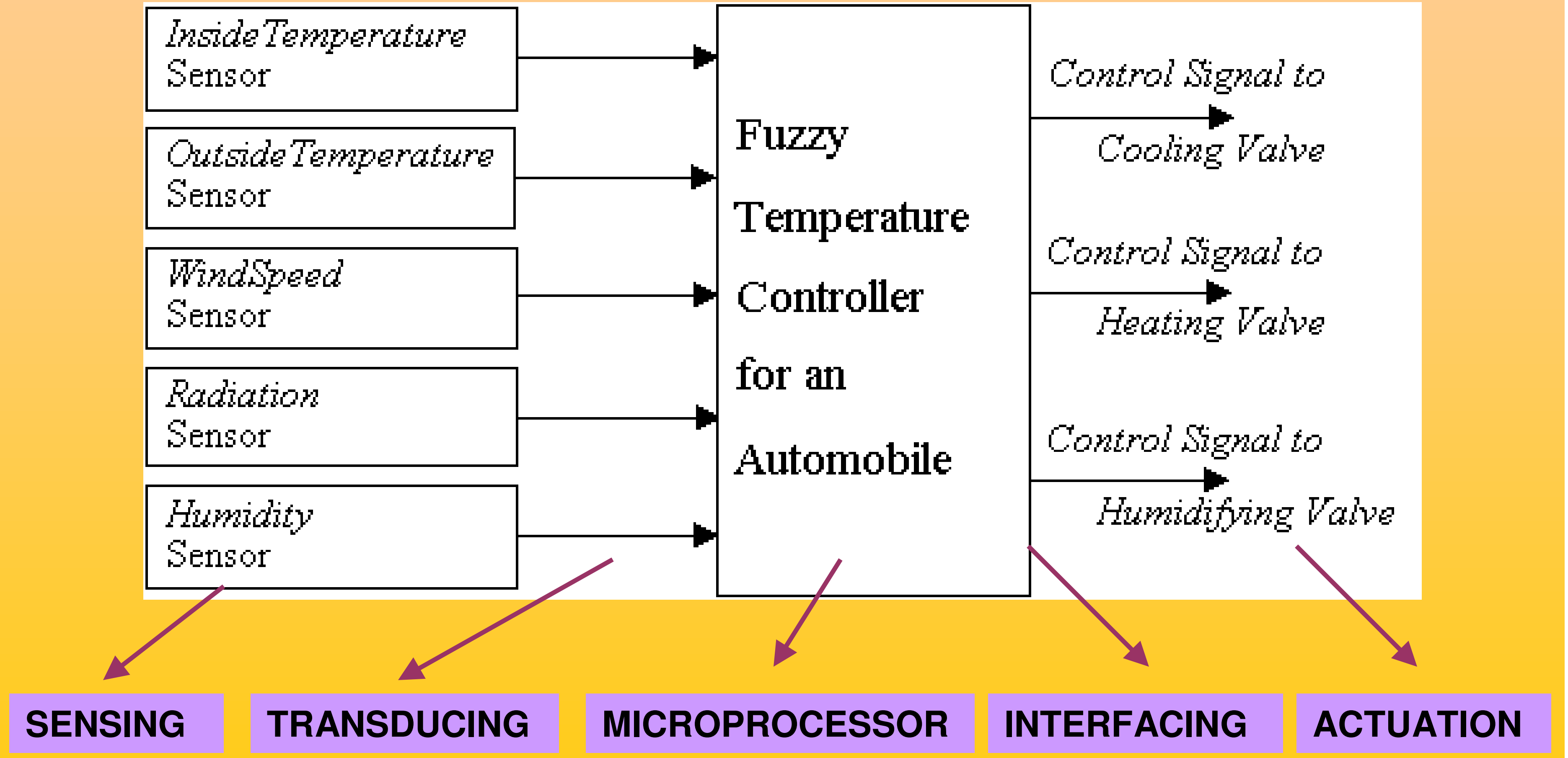
→ INTEGRATION

EXAMPLE OF SENSING AND ACTUATION: TEMPERATURE REGULATION

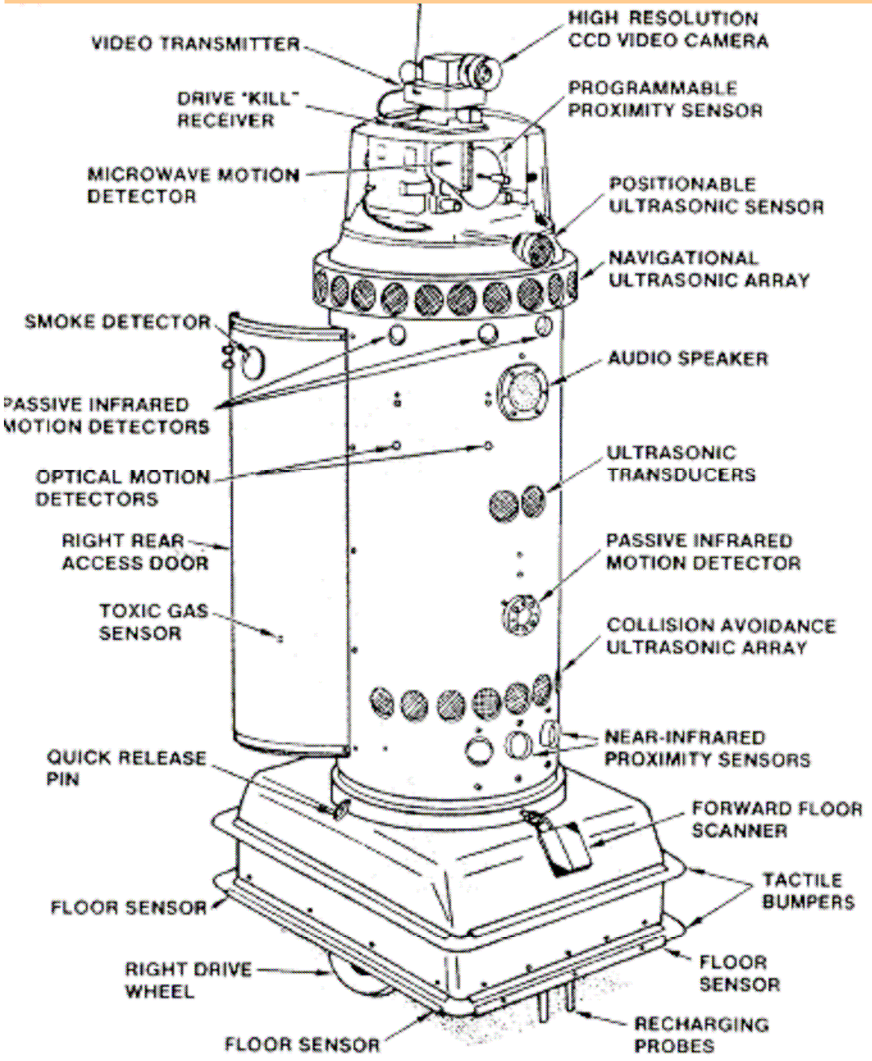
"classically"

EXAMPLE OF SENSING AND ACTUATION: TEMPERATURE REGULATION

"modernly"



PARADISE FOR SENSING AND ACTUATION: ROBOTS



Robot Sensors	Inner-State	Potentiometers		
		Synchros & Resolvers		
		Optical Encoders	Incremental	
			Absolute	
		Hall-Effect		
	Surface	Switches	Microswitchs	
			Pneumatic Touch Sensor	
			Digital Tactile Sensor Array	
		Piezoresistive	Conductive Elastomers	
			Carbon Felt & Carbon Fibers	
		Piezoelectric Polymers		
		Optical Sensors	Frustrated Internal Reflection	
			Opto-Mechanical	
		Ultrasonic		
		Capacitive		
		Electrochemical		
	External-State	Ranging (Distance)	SONAR	
			LIDAR	IR (Infrared)
				Laser
			RADAR	
		Vision Systems		

LIDAR (LIght Direction And Ranging)

LADAR (RAdio Direction And Ranging)

...LIFE OF SENSING AND ACTUATION CAN BE VERY COMPLEX

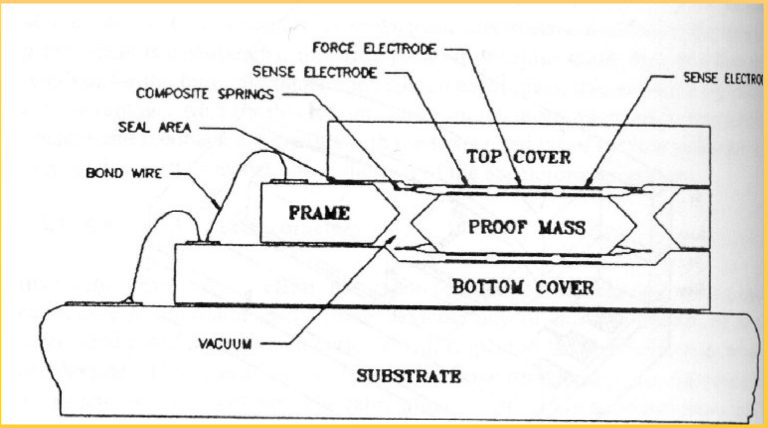
INTEGRATION OF SMALL SENSORS AND ACTUATORS: MICROELECTROMECHANICAL SYSTEMS (MEMS)

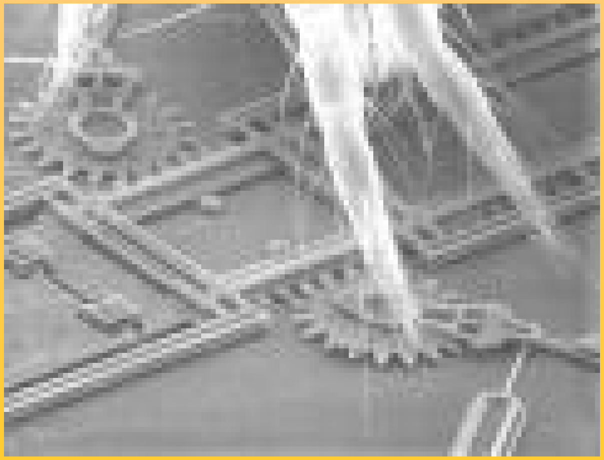
MEMS FOR SENSING:

* PRESSURE SENSORS
* ACCELEROMETERS
* FLOW SENSORS

MEMS FOR ACTUATION:

* MICROVALVES
* MICROMOTORS
* INKJET PRINTERS



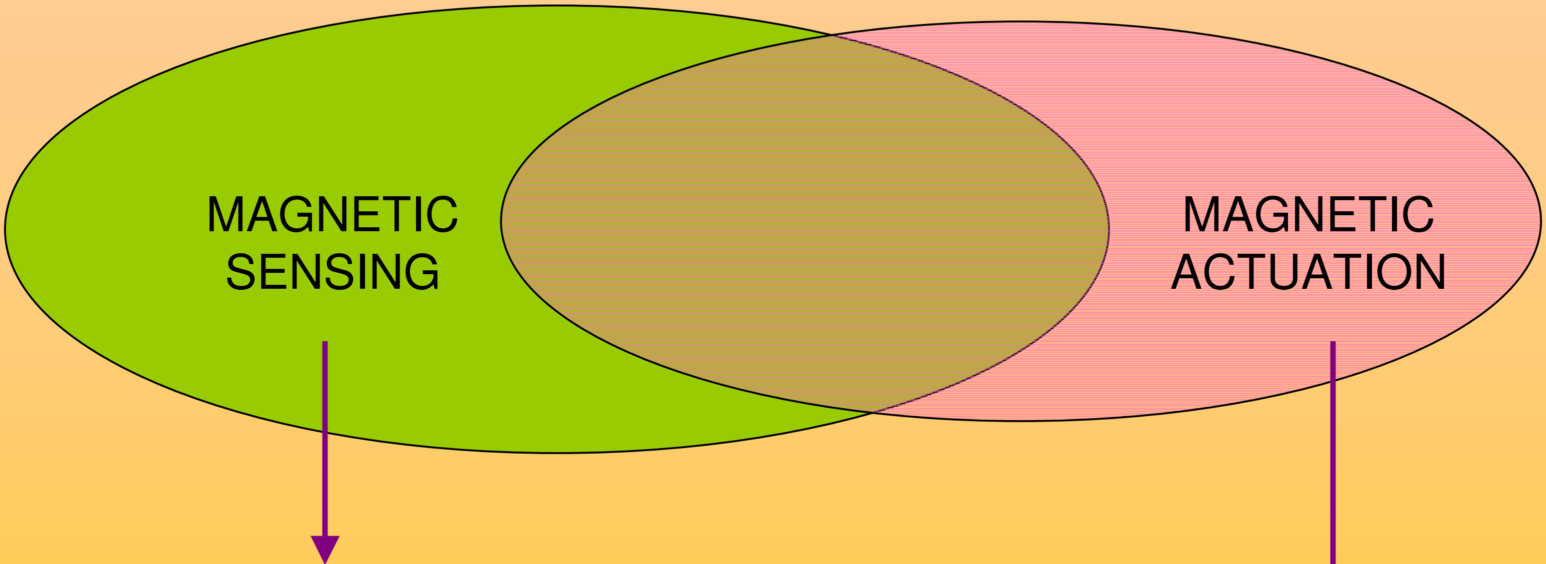


RELEVANT ASPECTS OF MEMS:

* THEY USE INFRASTRUCTURE AND TECHNOLOGY ALREADY EXISTING FROM THE INDUSTRY OF INTEGRATED CIRCUITS
* LARGE POTENTIAL MARKET EVEN THOUGH STANDARIZATION IS REQUIRED

INTRODUCTION TO MAGNETIC SENSING AND ACTUATION

MAGNETIC SENSING AND ACTUATION



-INDUCTIVE SENSORS

-HALL SENSORS

-MAGNETORESISTIVE SENSORS

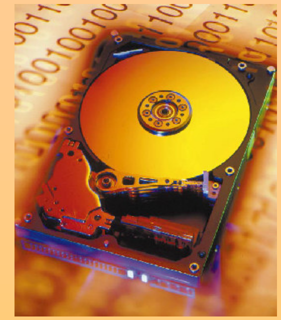
-SQUID SENSORS

Input electrical energy in the form of voltage and current is converted to magnetic energy, which produces a magnetic force able to generate motion.

Cluj school, September 2007

AUTOMOTIVE INDUSTRY

AERONAUTICS

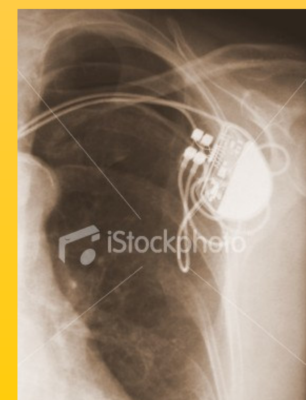


COMPUTER DISK DRIVES

MANUFACTURING INDUSTRY

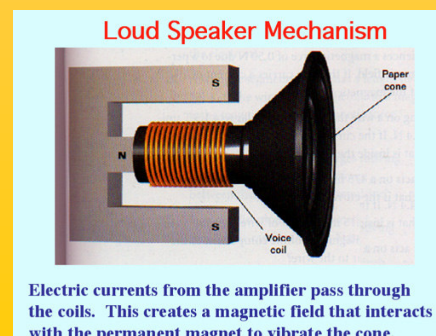
OVERVIEW OF THE APPLICATION OF MAGNETIC SENSORS AND ACTUATORS

BIOMEDICAL PROSTHESIS

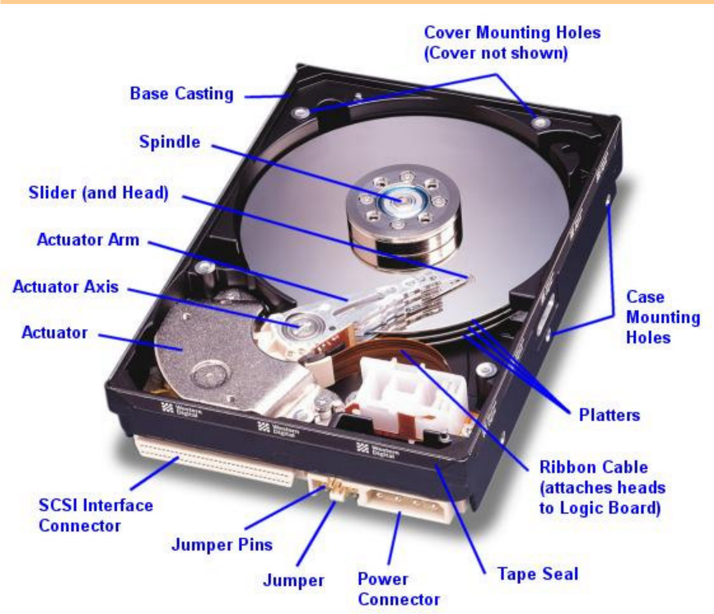


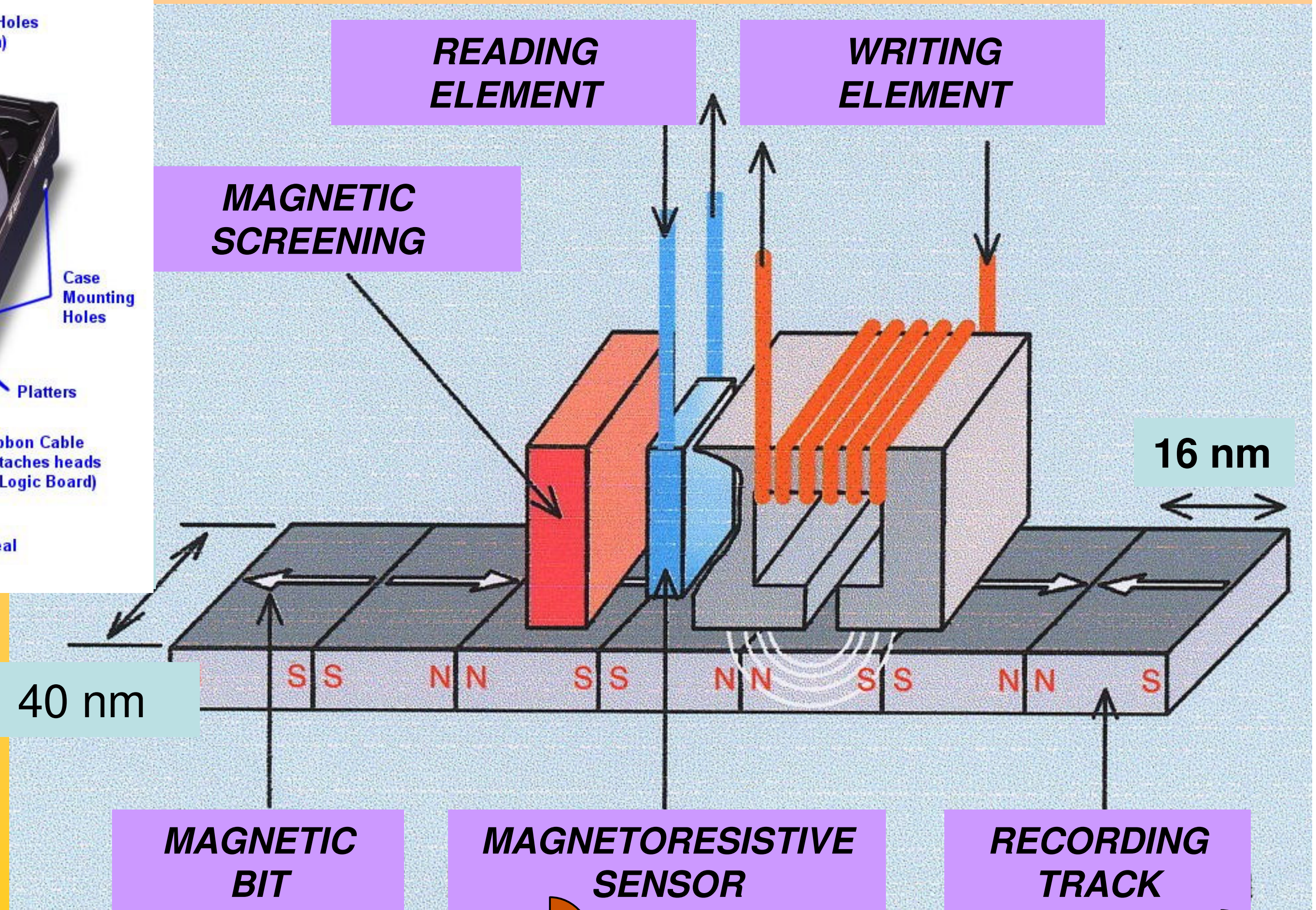
SONARS

LOUDSPEAKERS

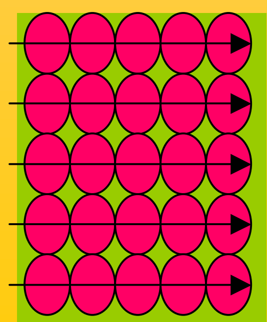


EXAMPLE OF MAGNETIC SENSING AND ACTUATION





bit



Based on GMR or TMR

Continuous layer with a Co-based alloy bearing 15 nm grains

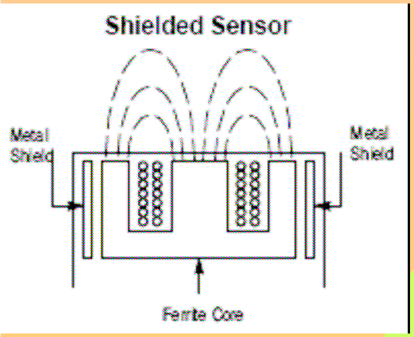
COMPARISON OF MAXIMUM ENERGY DENSITY OF VARIOUS ACTUATION MECHANISMS

Actuation	Max. energy density	Physical & material parameters	Estimated conditions	Approximate order (J/cm3)
Electrostatic	$\frac{1}{2} \varepsilon_0 E^2$	E = electric field ε_0 = dielectric permittivity	5 V/μm	~ 0.1
Thermal	$\frac{1}{2} Y (\alpha \Delta T)^2$	α = coefficient of expansion ΔT = temperature rise Y = Young's modulus	3×10^{-6}/° C 100° C 100 GPa	~ 5
Magnetic	$\frac{1}{2} B^2/\mu_0$	B = magnetic field μ_0 = magnetic permeability	0.1 T	~ 4
Piezoelectric	$\frac{1}{2} Y (d_{33} E)^2$	E = electric field Y = Young's modulus d_{33} = piezoelectric constant	30 V/μm 100 GPa 2×10^{-12} C/N	~ 0.2
Shape-memory alloy	—	Critical temperature		~ 10 [from reports in literature]

[1] Actual energy output may be substantially lower depending on the overall efficiency of the system.

MAGNETIC SENSING

MOST RELEVANT TYPES OF MAGNETIC SENSORS

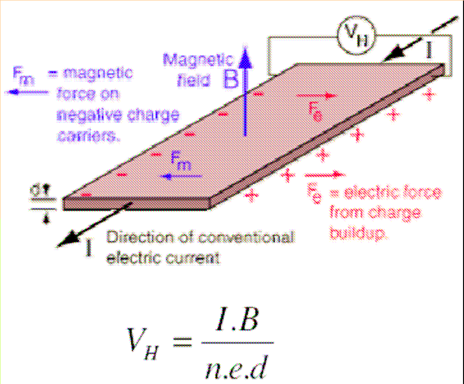


The induced voltage is

$$V = -N\frac{dBA}{dt}$$

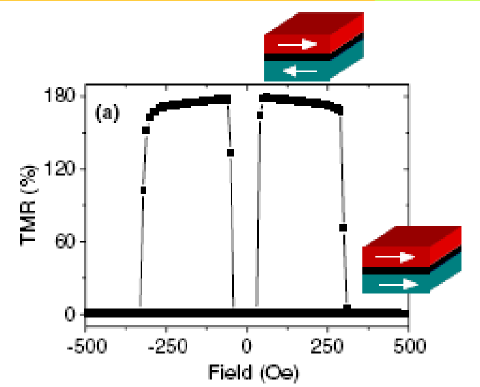
INDUCTIVE

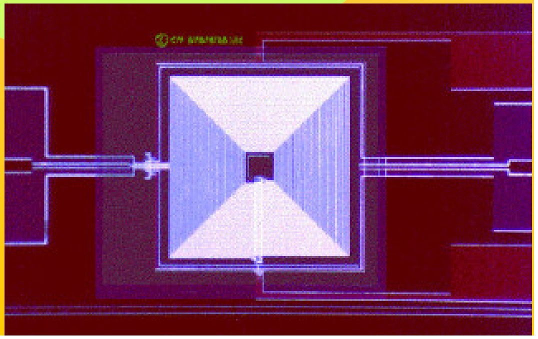
HALL

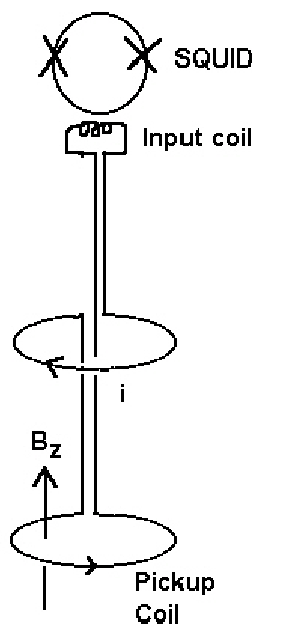


MAGNETO RESISTIVE

SQUID



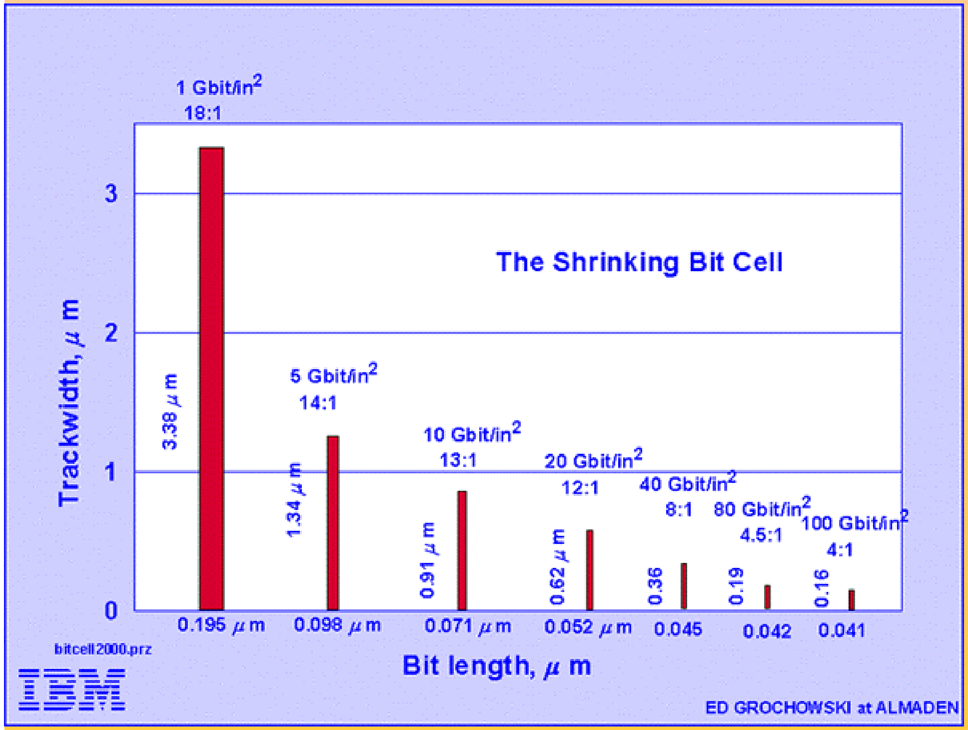


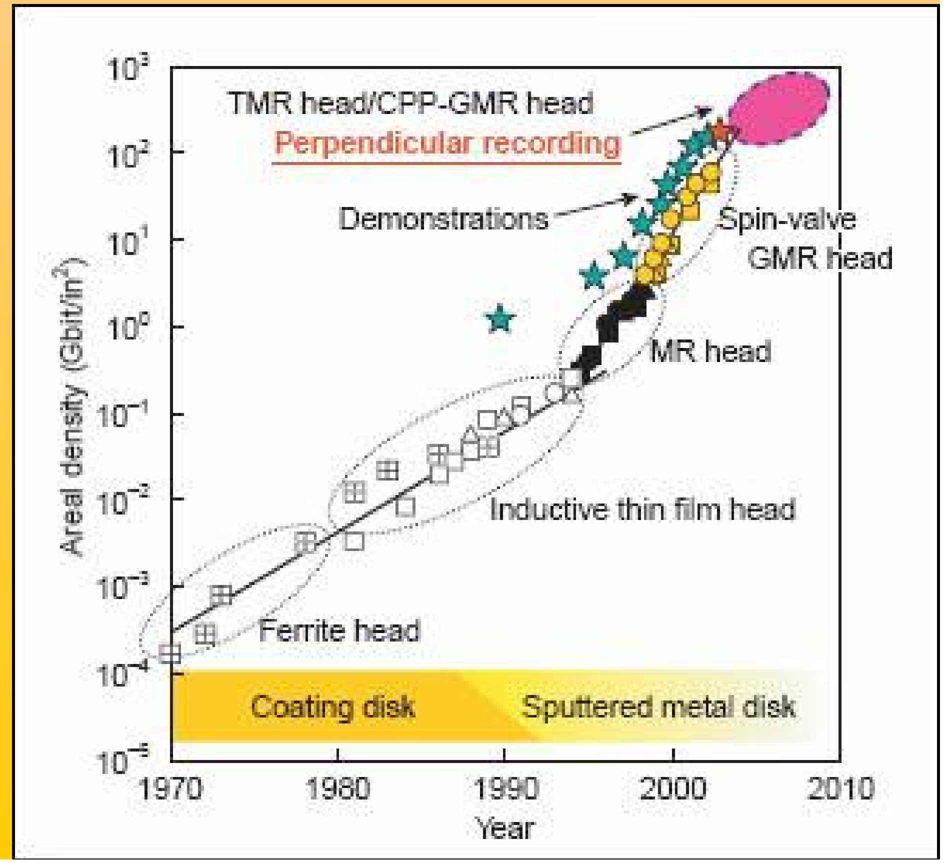


ROUGH COMPARISON OF MAGNETIC SENSORS

Type of sensor	**INDUCTIVE**	**HALL**	**MAGNETO-RESISTIVE**	**SQUID**
sensitivity	average	average nT range	good pT range	very good fT range
Handling	easy but not integrated	easy	easy	not easy (low temperature)
Cost	cheap	cheap	less cheap	much less cheap

IMPORTANCE OF MR SENSORS IN THE STORAGE DENSITY INCREASE



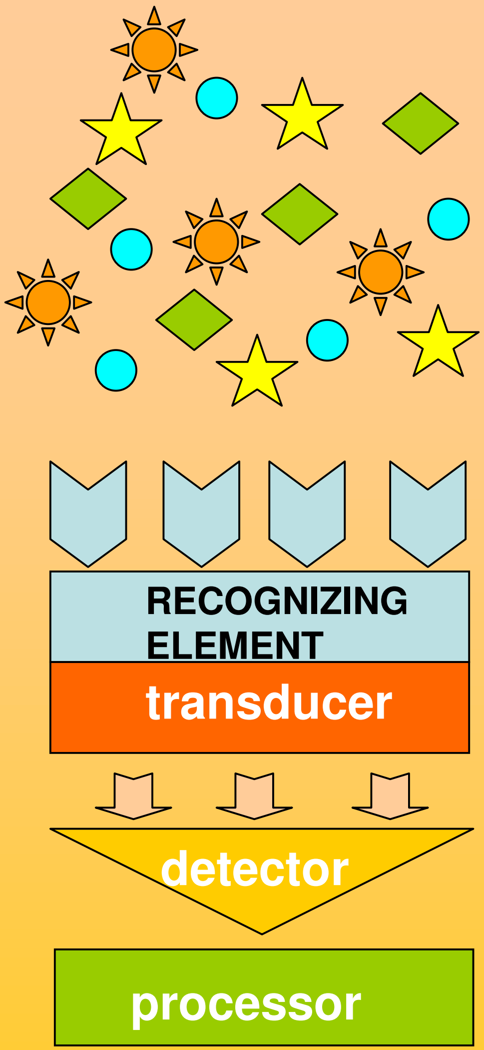


LATEST LOW-FIELD MAGNETORESISTIVE SENSORS

SpinTJ Magnetic Field Microsensors : Key Parameters	
Active Area Dimensions	2-15 μm^2
Active Area Thickness	3-12 nm
Field Noise Equivalent (100 Hz)	100 nT/Hz$^{1/2}$
Field Noise Equivalent (> 20 kHz)	5 nT/Hz$^{1/2}$
Total Magnetoresistance	80-200%
Hysteresis (1 G Sweep Range)	0.01 G
Non-linearity (1 G Sweep Range)	0.25%
Field Sensitivity	0.1-1.0 %/G (resistance change)
Sensor Impedance	Customizable from 10-10^{6}Ω

http://micromagnetics.com/

MAGNETIC BIOSENSORS



BIOSENSOR

Compact analysis device including:

Biological recognizing element
(Ab, DNA, enzyme, cell...)

+

Transduction system

Interaction / Hybridization
Targeted (bio)molecule – Recognizing element

Variation of physical/chemical properties
(pH, transfer of e-, magnetic or optical properties, etc.)

OUTPUT SIGNAL

Applications
- clinical diagnosis
- environment, agriculture
- chemical, farmaceutics and food industries
- military industry

Desired properties of a biosensor

- High sensitivity (mg/l, µg/l o mayor)
- High selectivity
- High fidelity: noiseless transducer
- Short analysis time – Real time analysis
- Miniaturization - Portable
- Automatization
- Simple handling
    - No high-profile personnel
    - No sample pre-treatment
- Long lifetime
- Reutilization
- Low production cost
- Multi-analysis capacity

CLASSIFICATION OF BIOSENSORS

Type of interaction
- Biocatalyst
- Bioaffinity

Detection of the interaction
- Direct
- Indirect

Recognition element
- Enzyme
- Tissue or complete cell
- Biological receptor
- Antibody
- Nucleic acids

Transduction system
- Electrochemical
- Optical
- Piezoelectric
- Thermometric
- Nanomecanical
- Electromagnetic

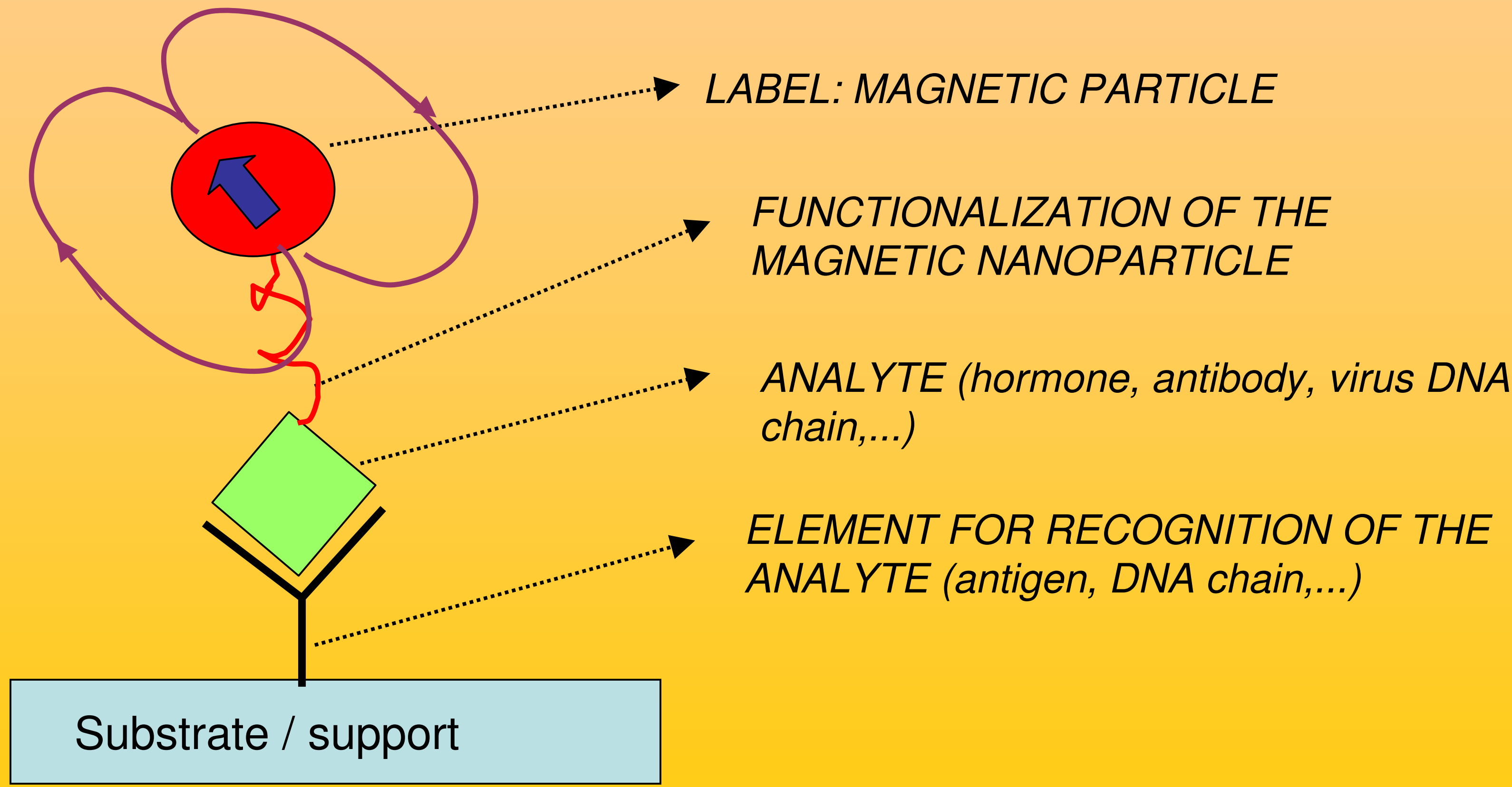
It depends on the characteristics of the targeted analyte

- **Lab-on-a- chip**

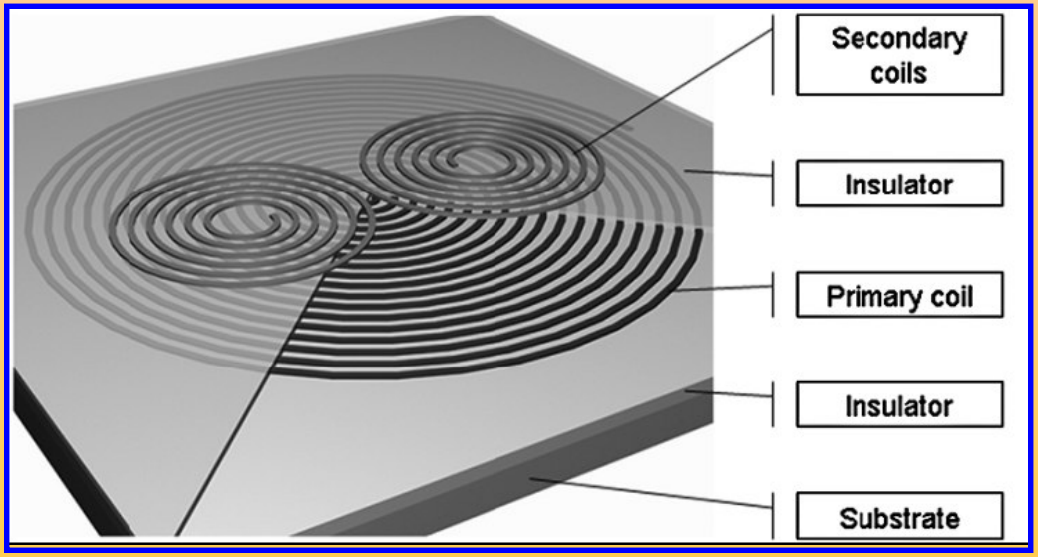
  This name has been coined for the systems where the sensor is integrated in the recognition platform, which favours miniaturization and efficiency

MAGNETIC BIOSENSORS

KEY CONCEPT: DETECTION OF THE MAGNETIC PARTICLES USED TO TAG THE RECOGNITION EVENTS



1) INDUCTIVE DETECTION OF THE MAGNETIC NANOPARTICLES

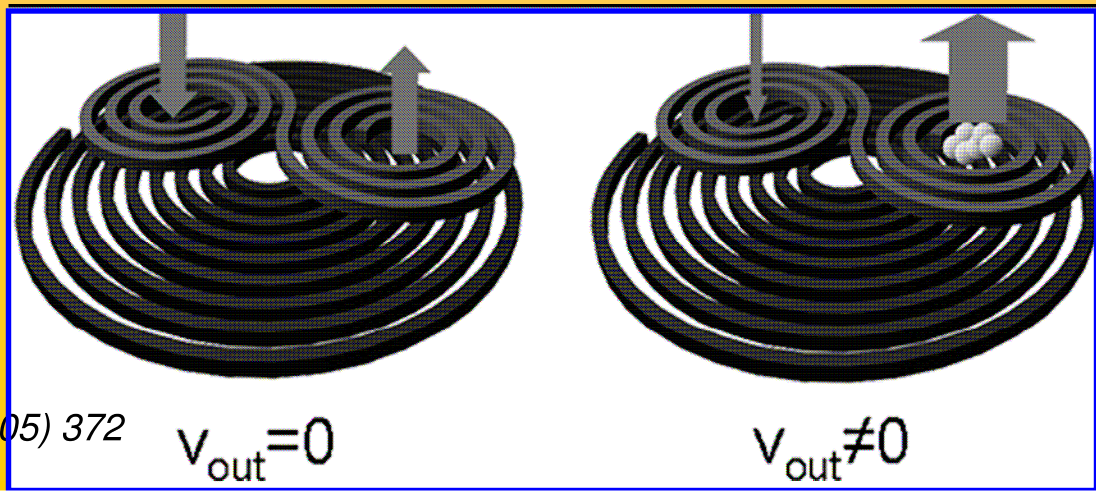


PRIMARY COIL: it creates an alternating magnetic field that polarizes the magnetic moment of the particles

SECONDARY COIL: an induced voltage occurs (Faraday and Lenz laws)

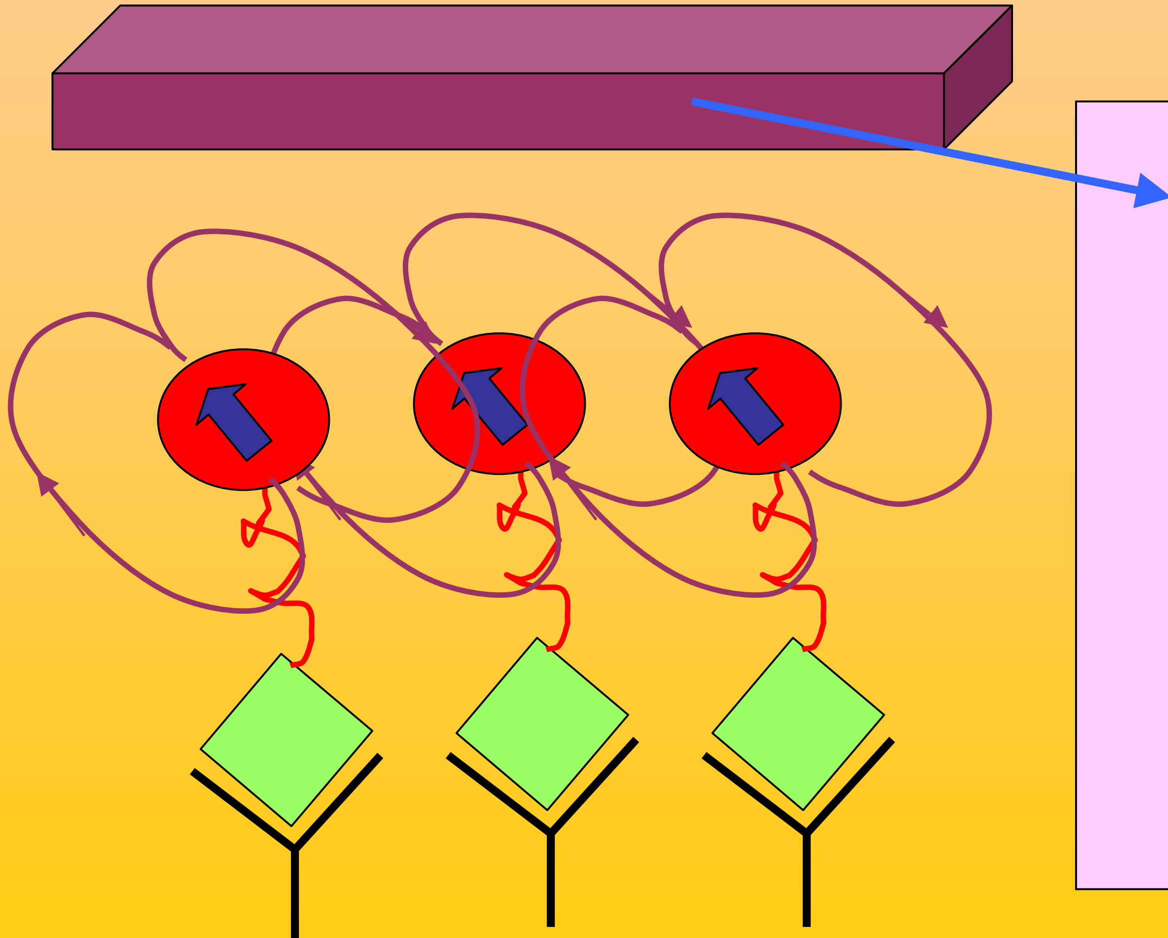
$$V_{induced} = -d\Phi/dt$$

Wound in series-oposition so that the captured magnetic flux be zero in the absence of magnetic nanoparticles



S. Baglio et al., IEEE Sensors Journal 5 (2005) 372

2) DETECTION OF THE DIPOLAR MAGNETIC FIELD PRODUCED BY THE NANOPARTICLES



HALL SENSOR

or

AMR SENSOR

or

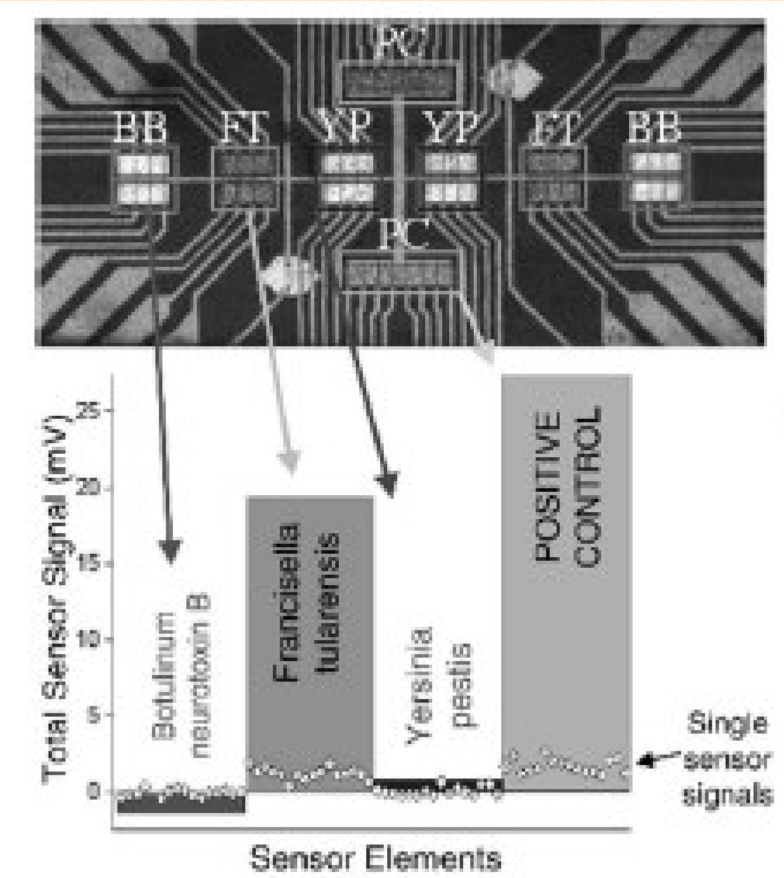
GMR SENSOR

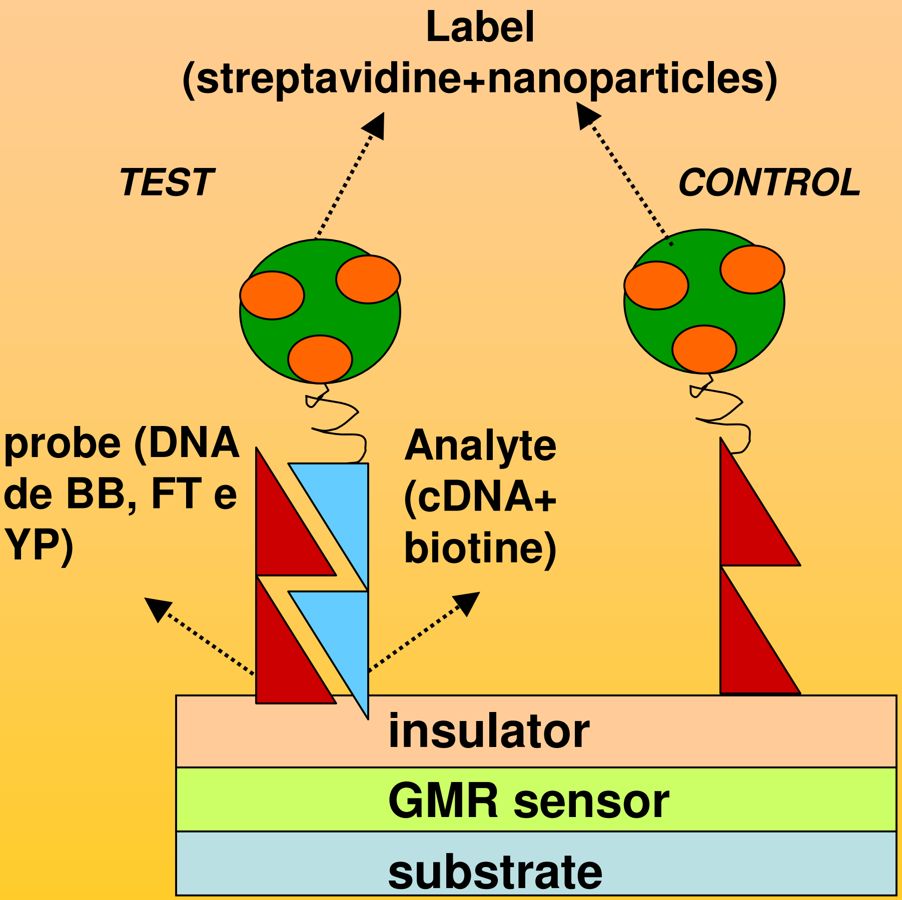
or

TMR SENSOR

EXAMPLE: LAB-ON-CHIP DETECTION OF BIOLOGICAL RECOGNITION VIA GMR SENSORS

DETECTION OF WARFARE AGENTS FOR CHEMICAL WAR BY MEANS OF A "BEAD ARRAY COUNTER"=BARC





THIS KIND OF TECHNOLOGY HAS BEEN APPLIED FOR THE DETECTION OF GENE MUTATIONS

Naval Research Laboratory: D.R. Baselt et al., Biosensors and Bioelectronics 13 (1998) 731; M.M. Miller et al., J. Magn. Magn. Mater. 225 (2001) 138; P.P Freitas et al., Europhysics News 34 (2003) 224

Magnetic biosensors. Application in lateral-flow tests.

J.M. De Teresa, C. Marquina, R. Ibarra, J. Sesé, J.A. Valero

(previously also D. Serrate y D. Saurel)

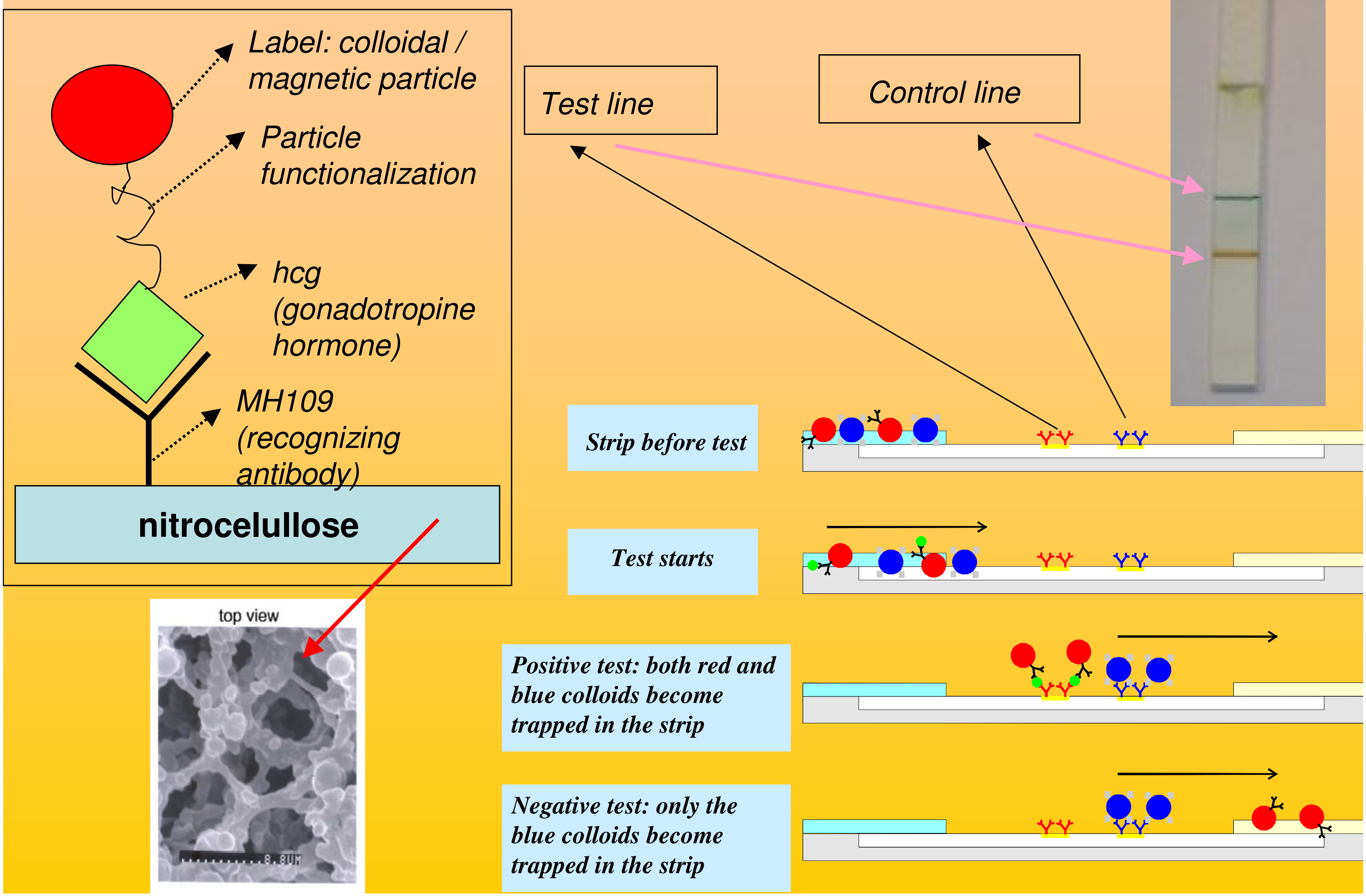
In collaboration with:

-R. Fernández-Pacheco, V. Grazú, etc.

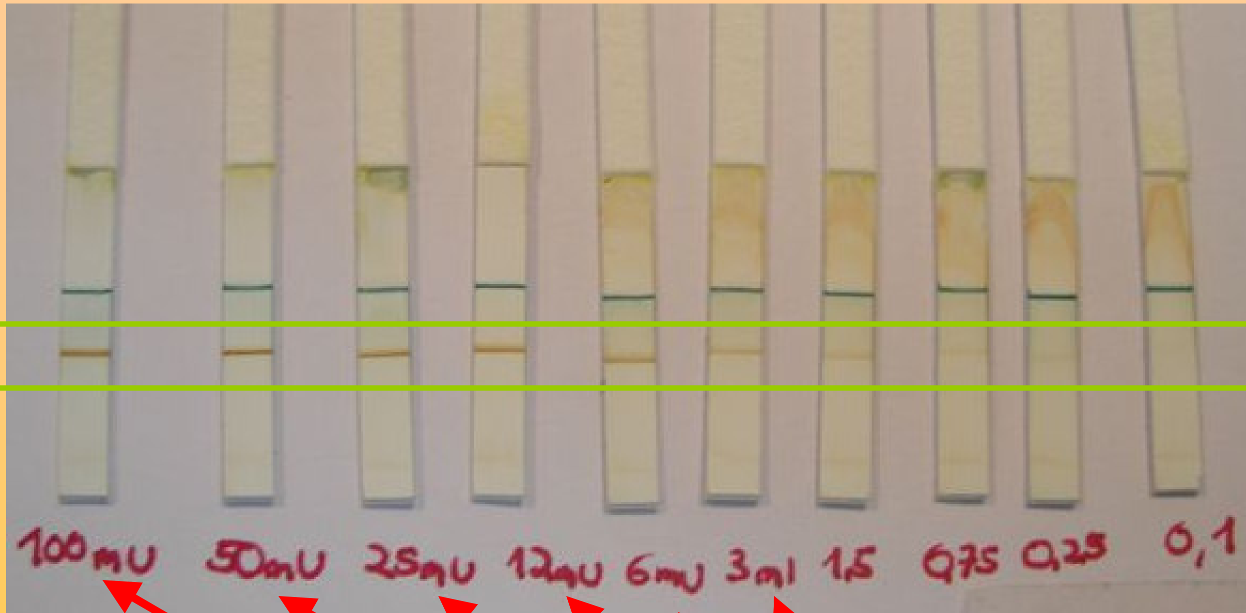
-P. Freitas (INESC, Lisbone)

-CerTest company (C. Génzor)

DESCRIPTION OF A LATERAL-FLOW TEST



OUR AIM IS TO PERFORM QUANTITATIVE AND HIGH-SENSITIVE DETECTION IN LATERAL-FLOW TESTS



**Use of commercial nanoparticles by ESTAPOR 30/40 10%*

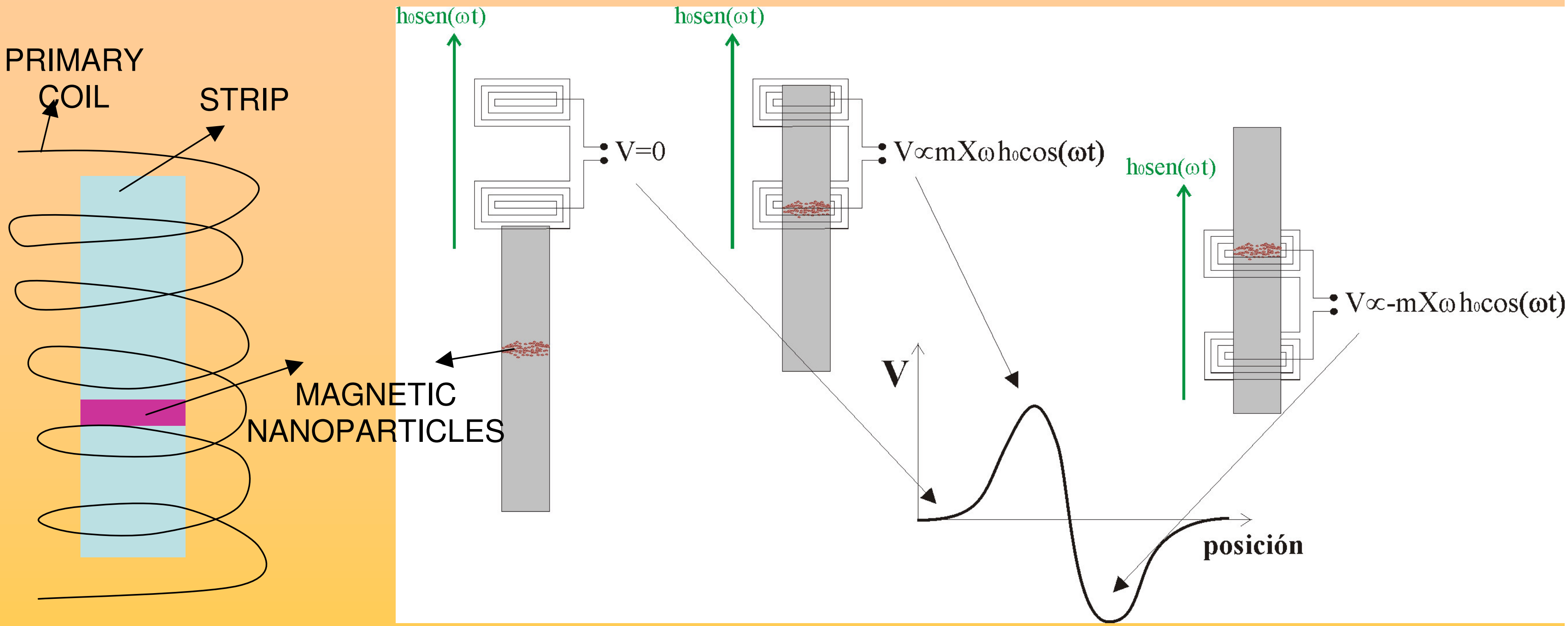
(diameter 300-500 nm with 30-60% ferrite and covered with polystyrene)

Funcionalization with sugar-like groups

Better result

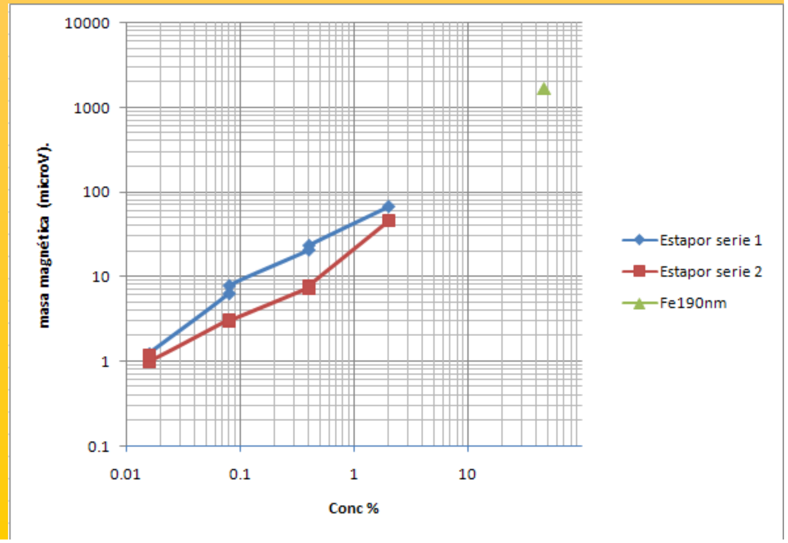
Funcionalization with amino groups

INDUCTIVE DETECTION IN LATERAL-FLOW TESTS



The output signal is proportional to the excitation amplitude, the frequency, the number of turns and filling factor and, of course, to the magnetic susceptibility of the magnetic nanoparticles

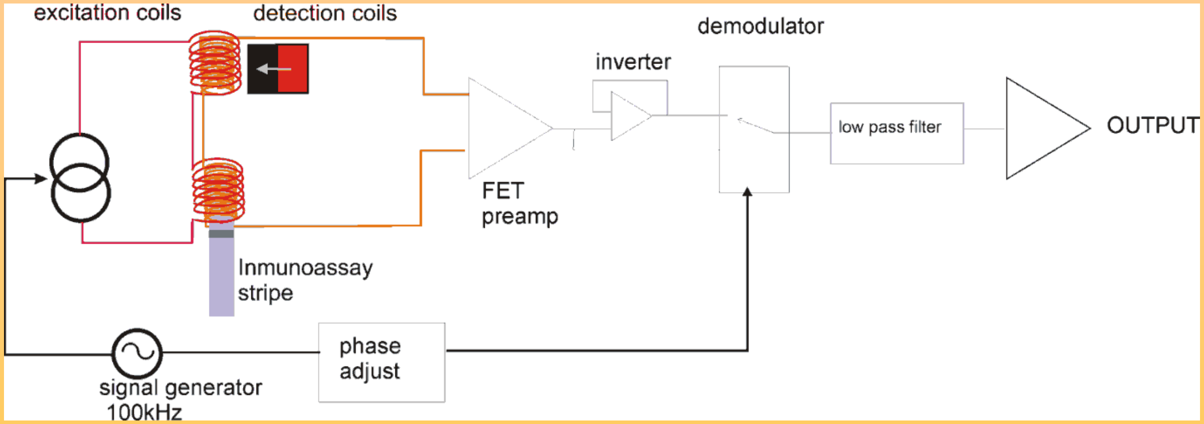
I=0.188Arms (30 Oe), 3.33kHz, Tc=100ms

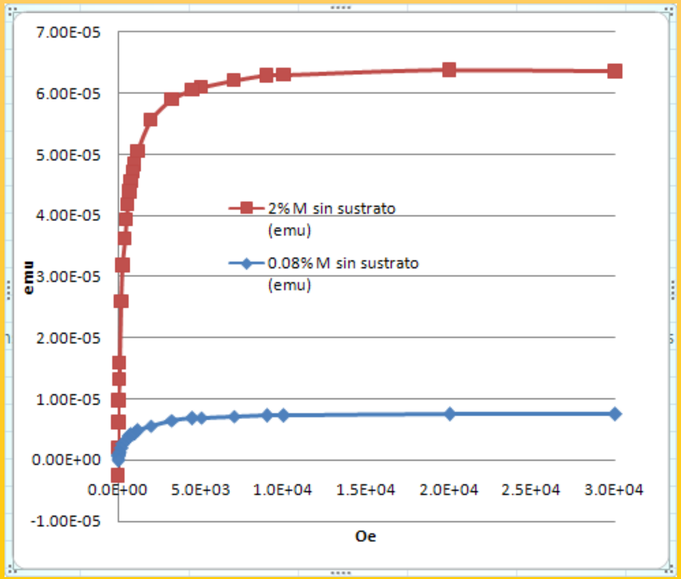


INDUCTIVE DETECTION IN LATERAL-FLOW TESTS

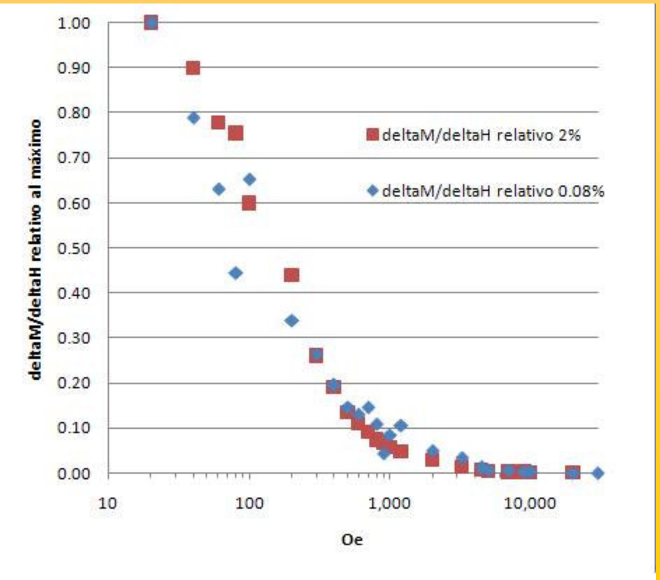
New sensor design:
•For standard lateral-flow nitrocellulose strips
•It allows independent measurement of the signal from particles and from surroundings

Patent P200603262



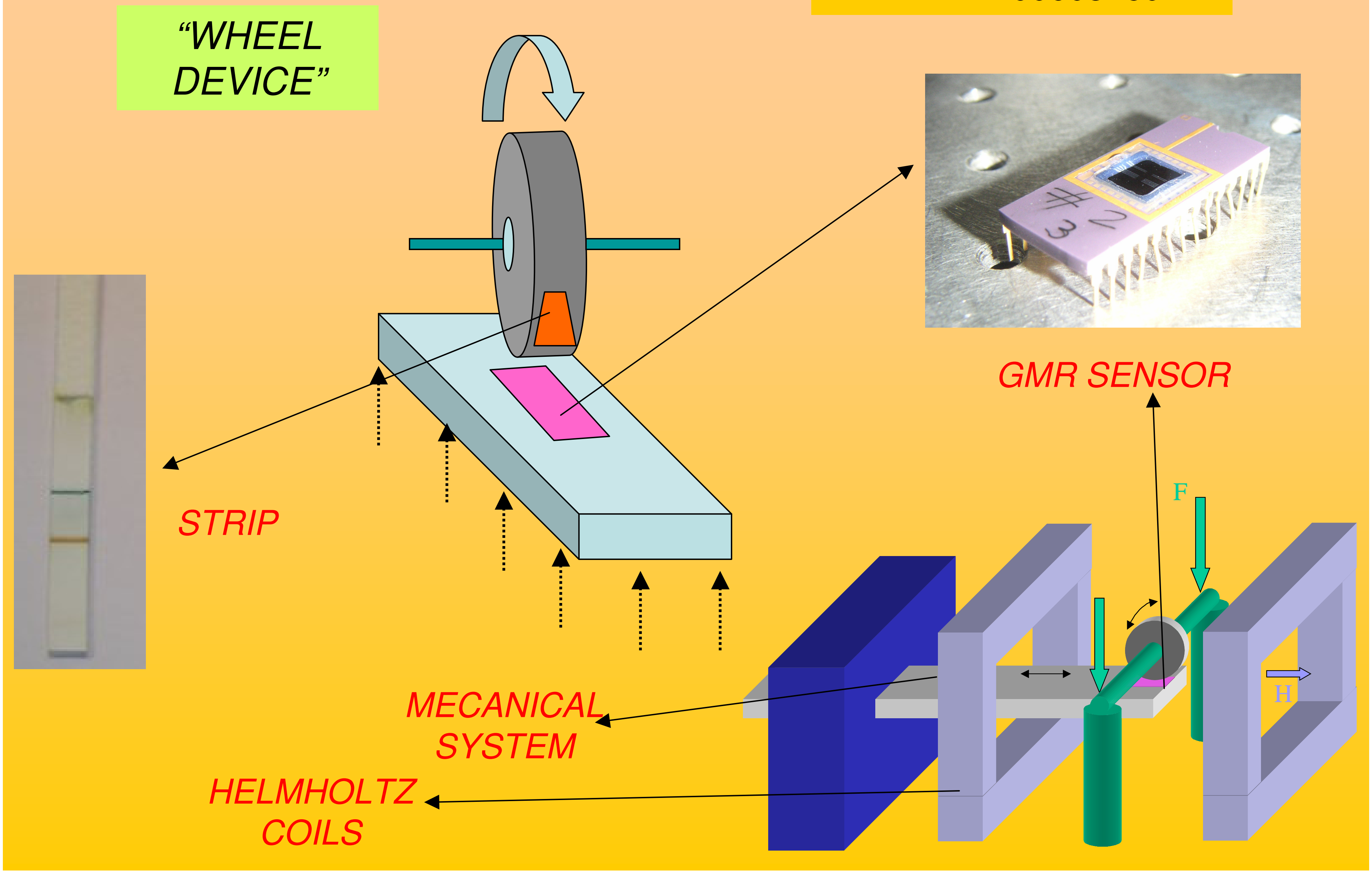


A magnetic field of 1000 Oe saturates the signal from the nanoparticles

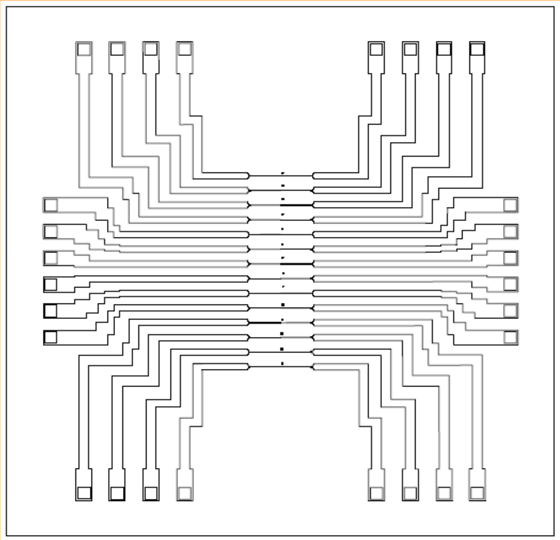


MAGNETORESISTIVE DETECTION IN LATERAL-FLOW TESTS

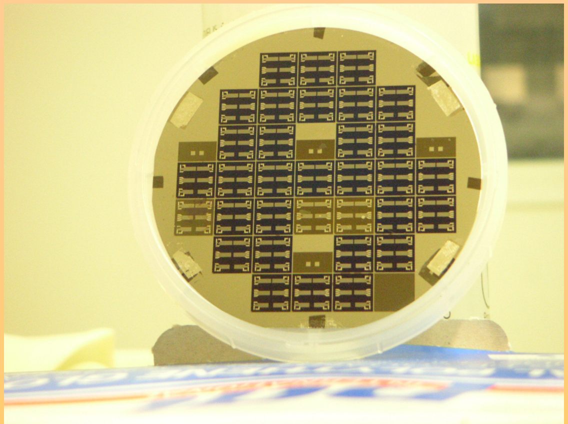
PATENT P200603259

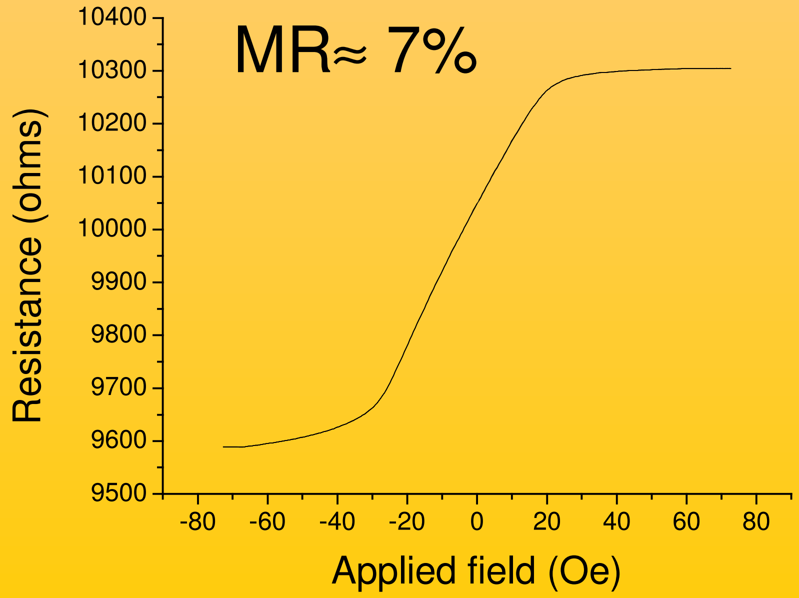


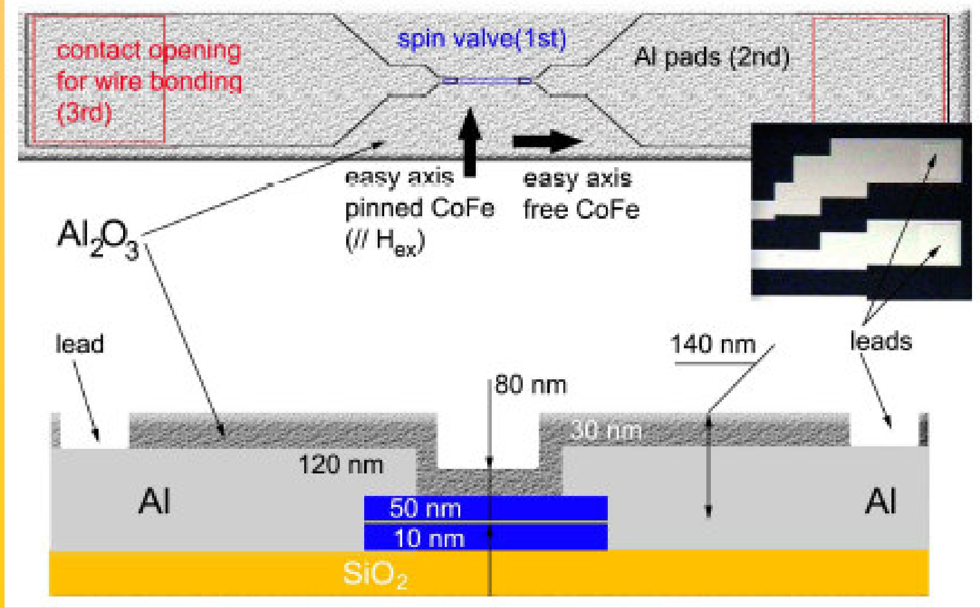
MAGNETORESISTIVE DETECTION IN LATERAL-FLOW TESTS



GMR SENSORS MICROFABRICATED IN INESC, LISBONE

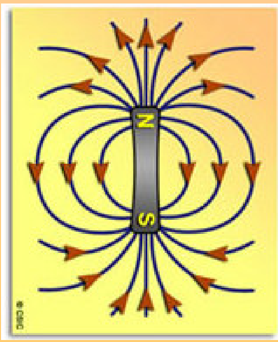


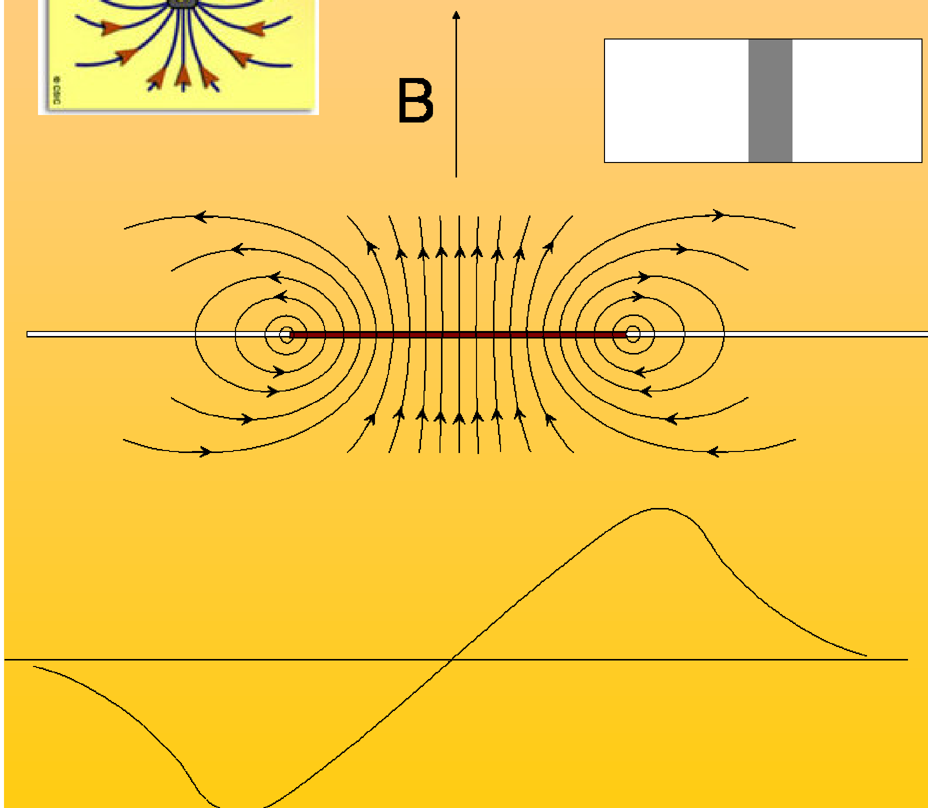


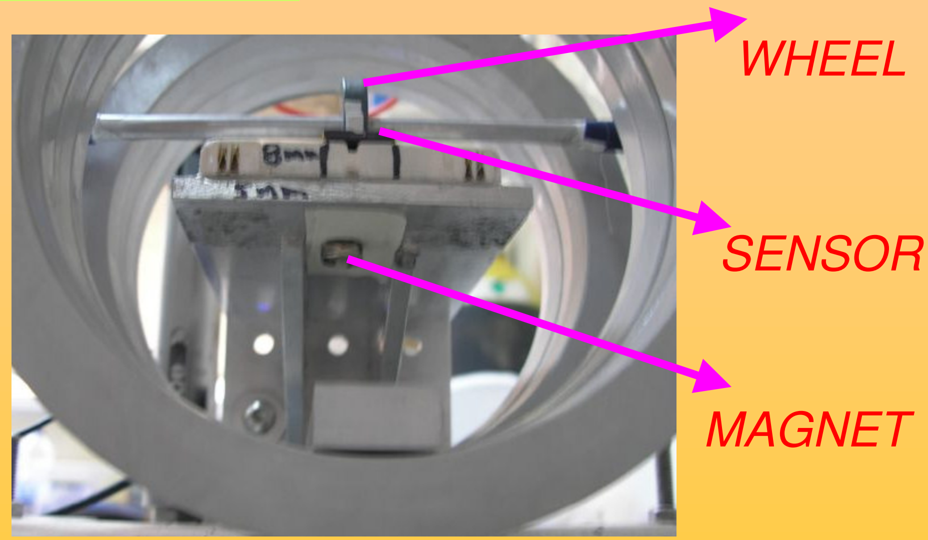


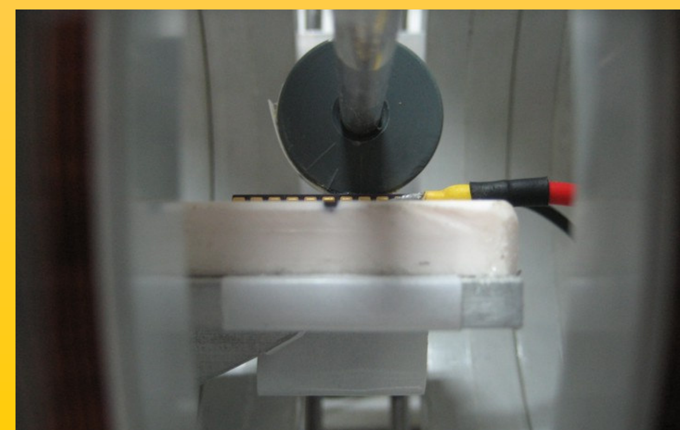
MAGNETORESISTIVE DETECTION IN LATERAL-FLOW TESTS

WE APPLY A PERPENDICULAR MAGNETIC FIELD BY MEANS OF A PERMANENT MAGNET TO AVOID THE USE OF HEMHOLTZ COILS



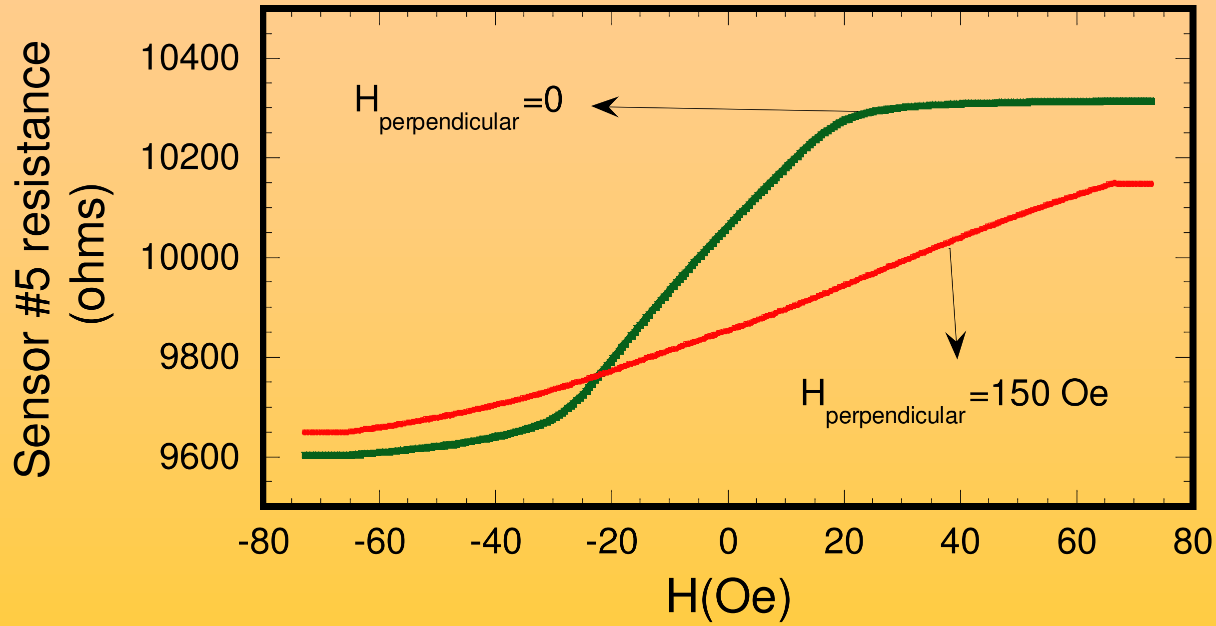


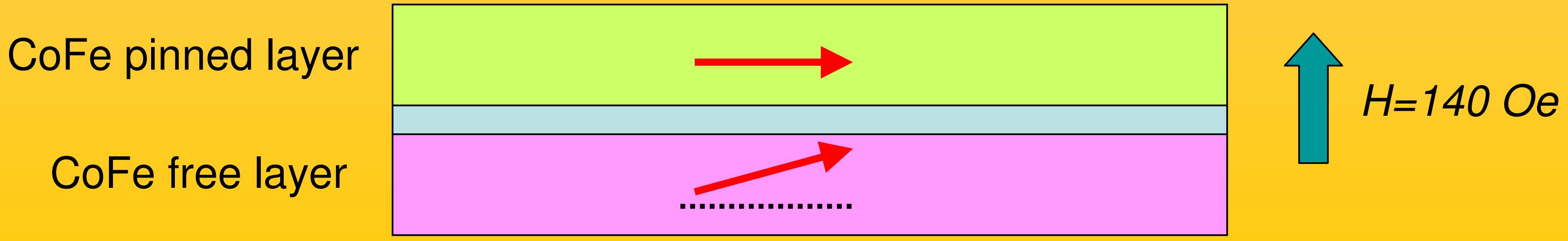




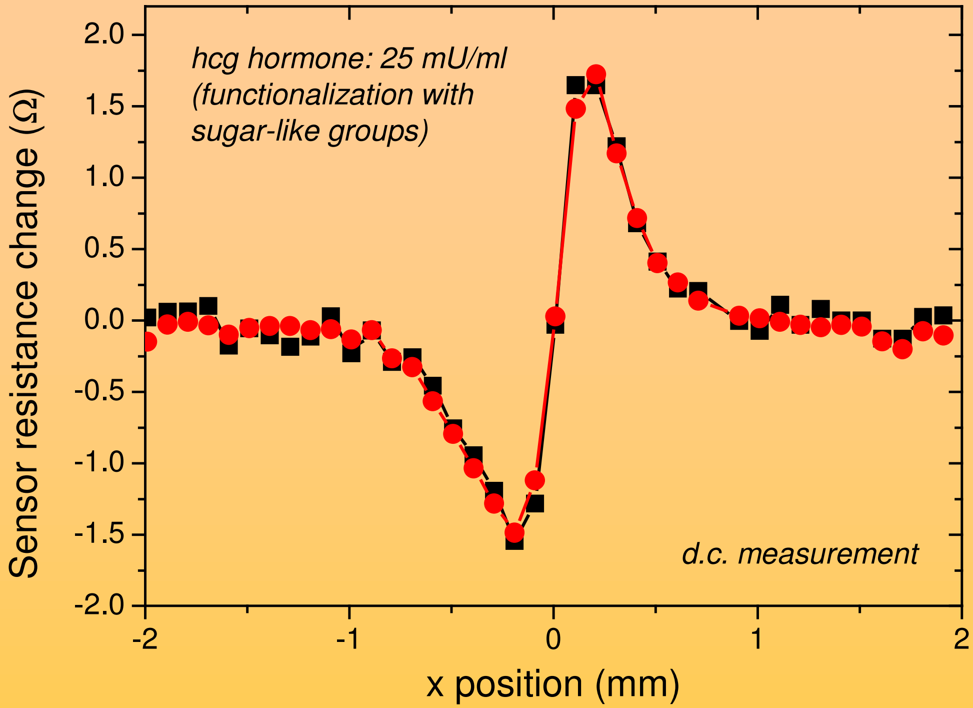
MAGNETORESISTIVE DETECTION IN LATERAL-FLOW TESTS

INFLUENCE OF THE PERPENDICULAR FIELD ONTO THE SENSOR RESPONSE

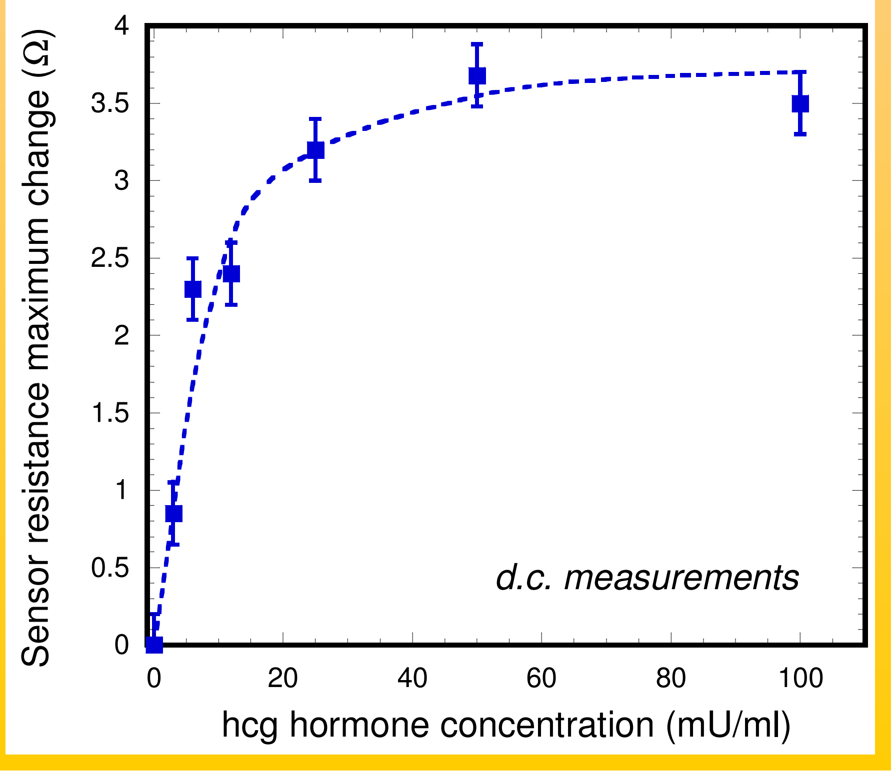




MAGNETORESISTIVE DETECTION IN LATERAL-FLOW TESTS

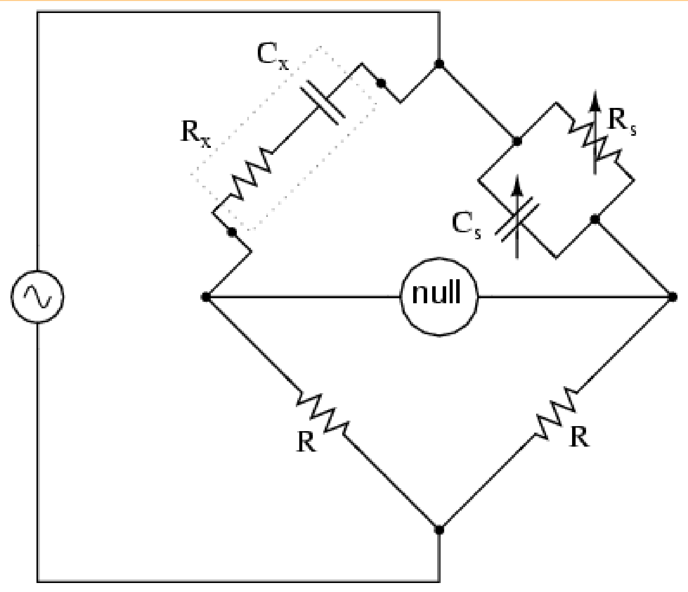


WE OBTAIN A QUANTITATIVE OUTPUT BUT BETTER SENSITIVITY IS REQUIRED



MAGNETORESISTIVE DETECTION IN LATERAL-FLOW TESTS

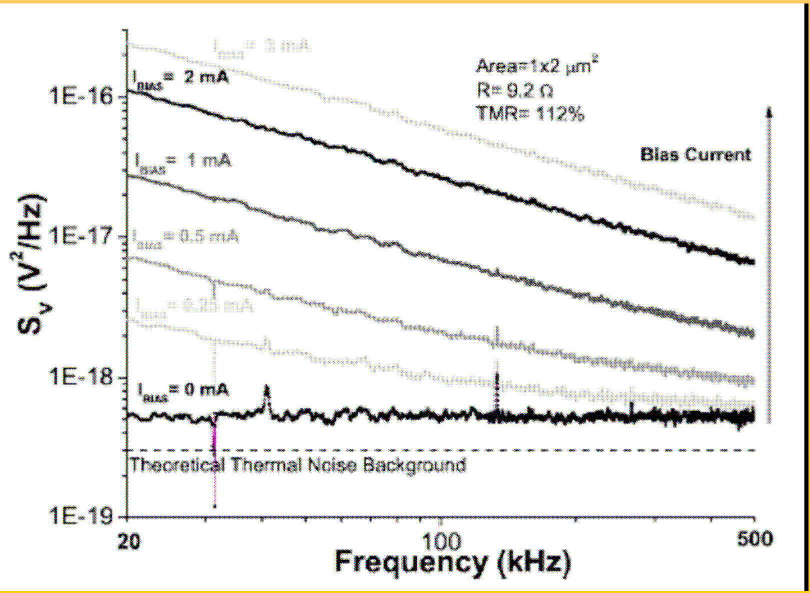
NEXT STEP: USE OF TMR SENSORS BASED ON MgO BARRIERS (MR~150%), WHICH MEANS 50 TIMES HIGHER SIGNAL, INTEGRATED ON ac WHEASTONE BRIDGES



***Noise sources*: thermal, shot, 1/f, magnetic**

The noise can be minimized working at high frequencies

$$S_V = \frac{\alpha_H I^2 R_{dut}^2}{A f} + k$$



Ferreira et al., J. Appl. Phys. 99, 08K706 (2006)

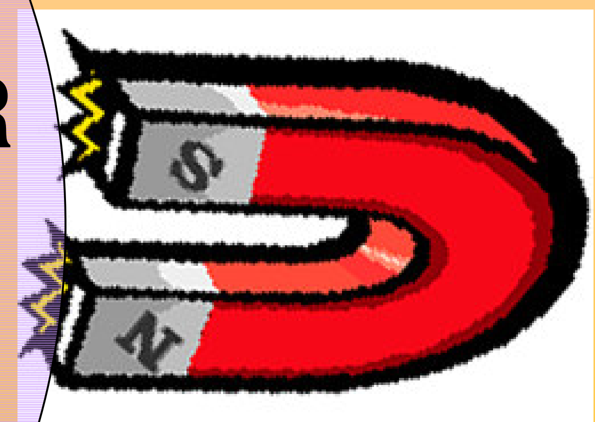
If we increase the signal to noise ratio, we expect to get high sensitivity in our magnetoresistive biosensor

CONCLUSIONS ANS PERSPECTIVES

MAGNETIC SENSING AND ACTUATION IS A WELL-ESTABLISHED TECHNOLOGY IN THE FIELD OF SENSING AND ACTUATION

ON TOP OF CLASSICAL APPLICATIONS, GREAT OPPORTUNITIES ARE OPEN IN THE FIELDS OF MEMS/NEMS AND IN MAGNETIC BIOSENSORS

THANKS FOR YOUR ATTENTION



LATEST NEWS:

FIESTA IS NOW ALLOWED!